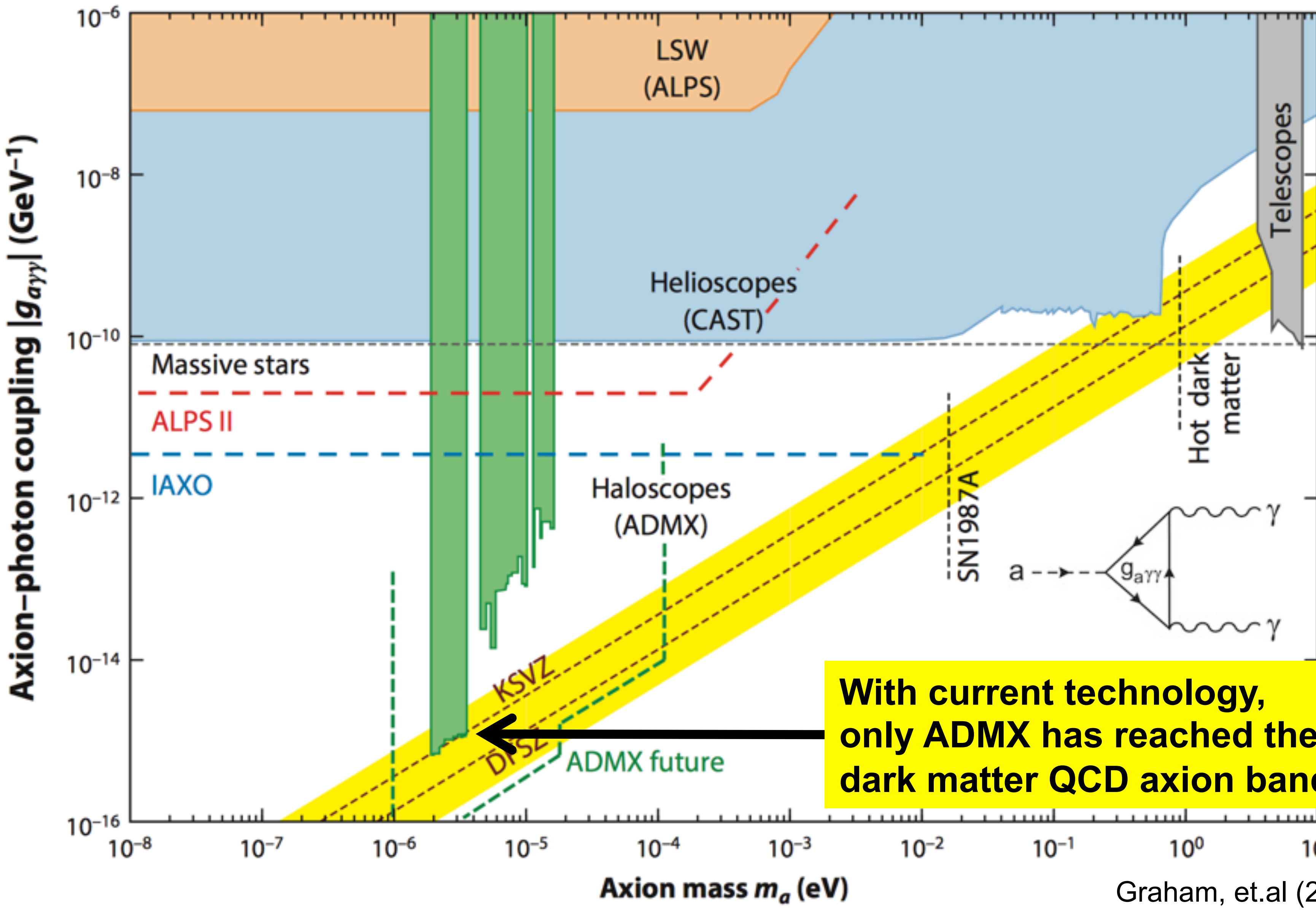
An Update on ADMX

Gianpaolo Carosi
LLNL

3rd Berkeley Workshop on Dark Matter Detection

Lawrence Berkeley National Laboratory

Axion experimentally constrained parameter space



With current technology, only ADMX has reached the dark matter QCD axion band.

Graham, et.al (2016)

ADMX: Collaboration (begin in mid-1990s)

University of Washington

UF University of Florida

Berkeley University of California

Lawrence Livermore National Laboratory

NRAO

The University Of Sheffield.

Recently Joined

Fermilab

Pacific Northwest National Laboratory

Washington University in St. Louis *

Los Alamos National Laboratory

Sponsors

ADMX now DOE Gen 2 project

Department of Energy

NSF

Heising - Simons Foundation

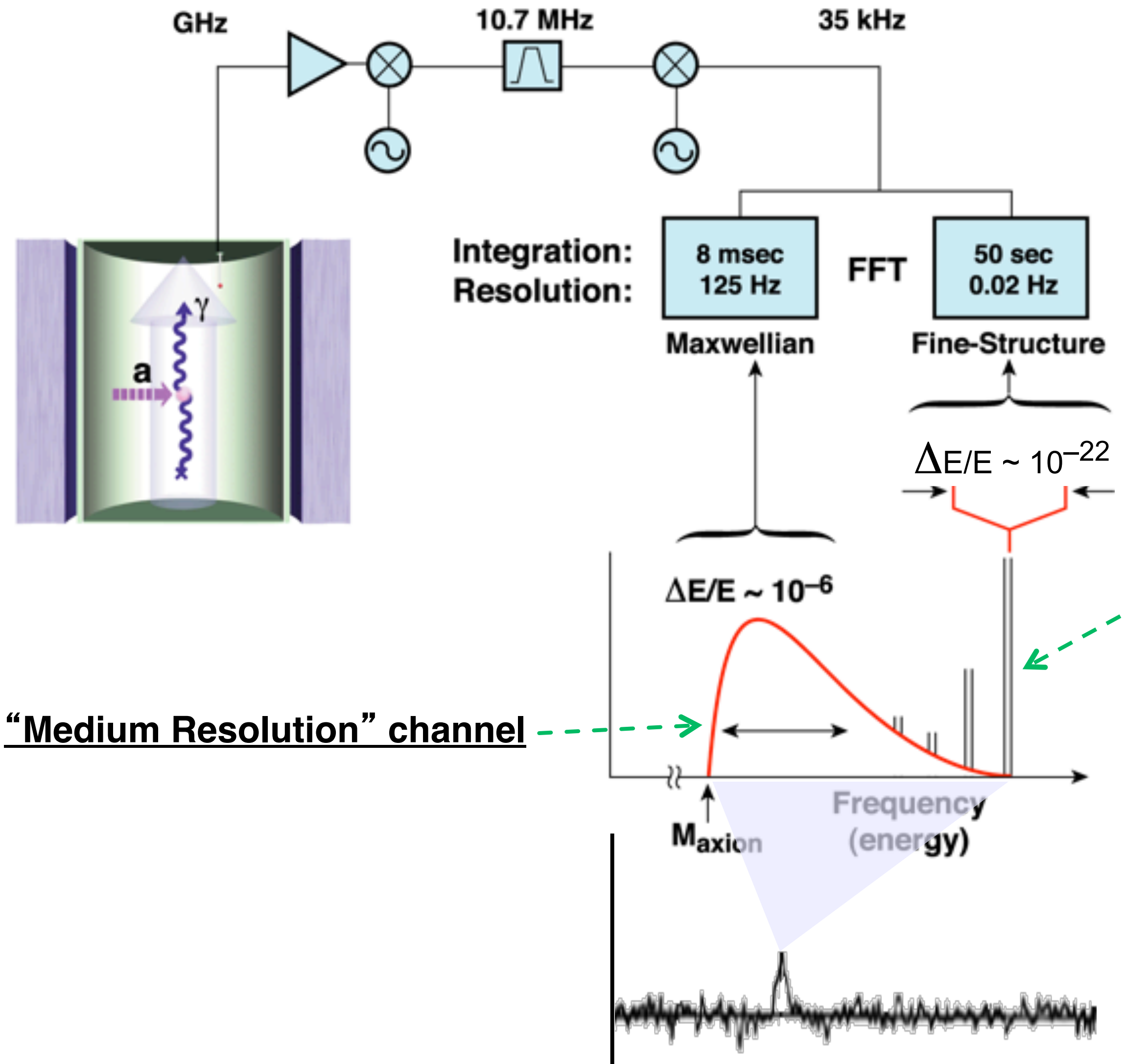
Primary sponsor

ADMX-High Frequency

Separate collaboration sited at Yale

*in process of joining

The ADMX experimental layout
(original concept from P. Sikivie)



Local Milky Way density:

ρ_{halo} ~ 450 MeV/cm^3

Thus for m_a ~ 10 μeV:

ρ_{halo} ~ 10^{14} cm^{-3}

"High Resolution" channel

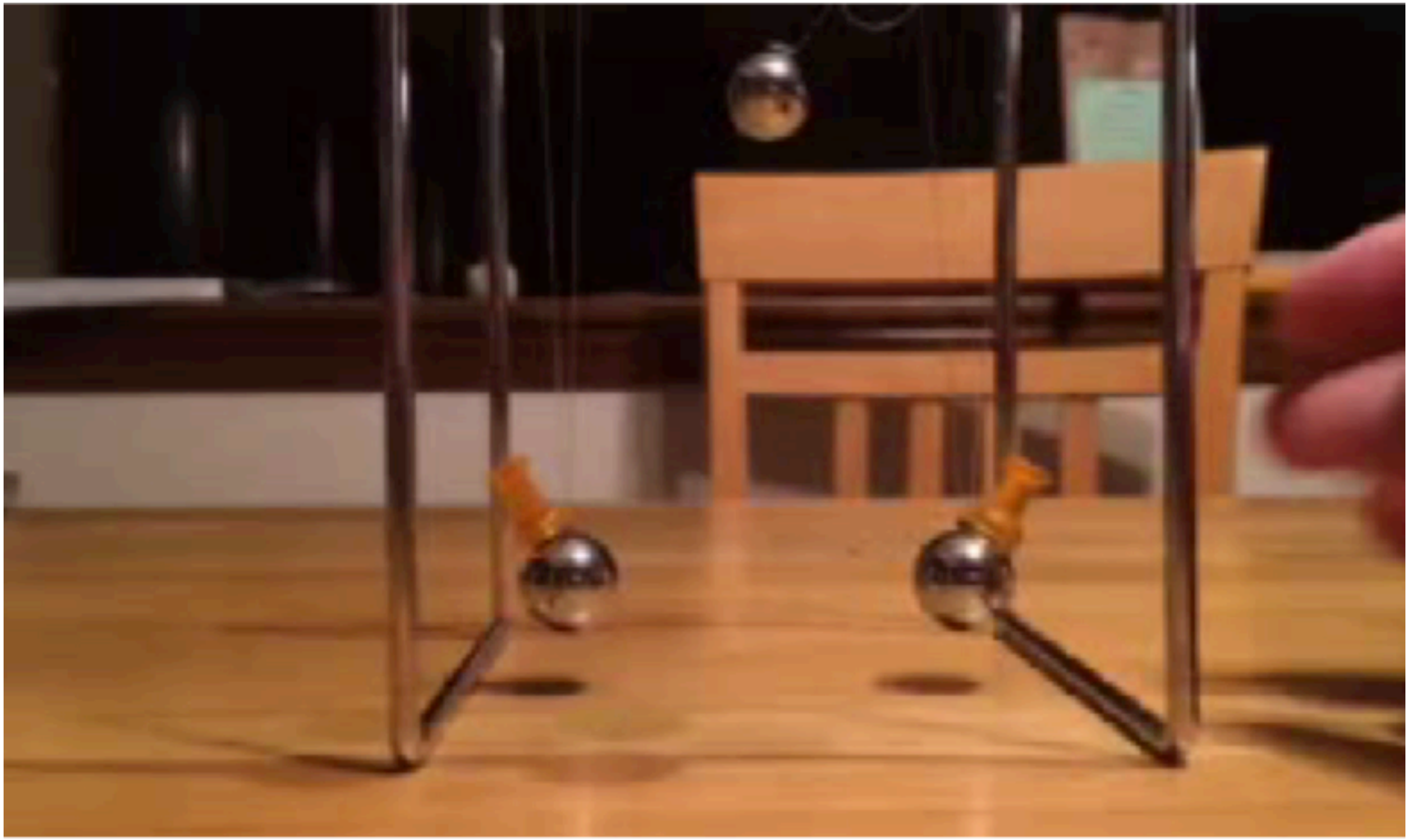
β_{virial} ~ 10^{-3} :

$\lambda_{\text{De Broglie}}$ ~ 100 m

$\Delta\beta_{\text{flow}}$ ~ 10^{-11} :

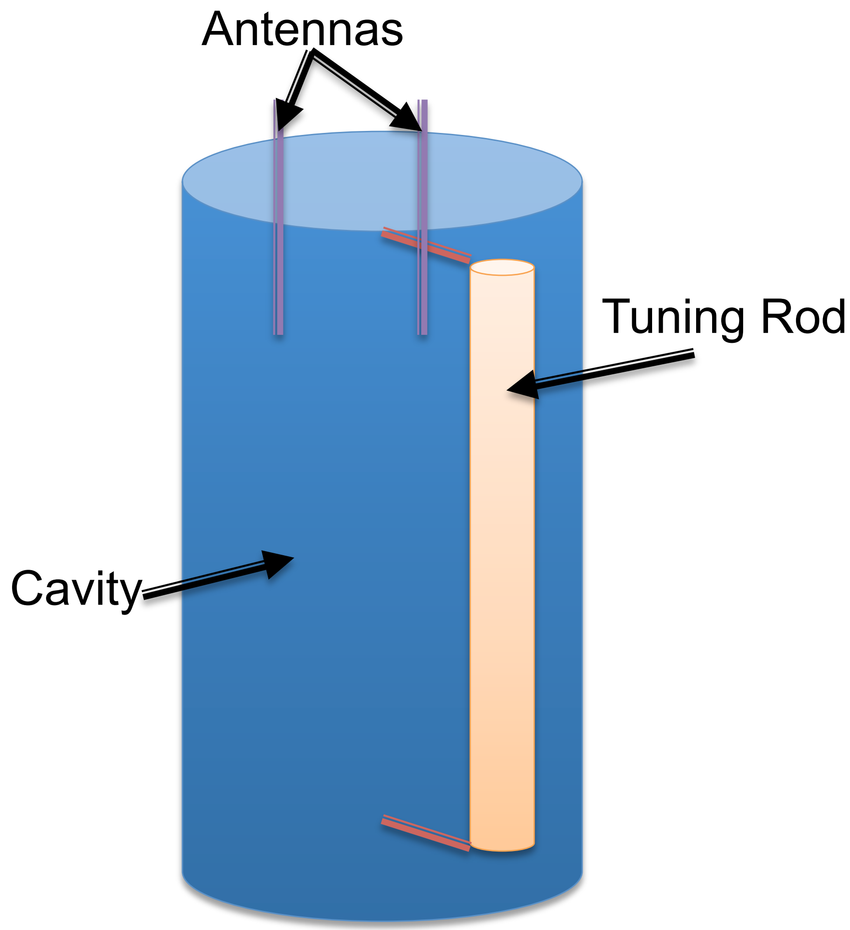
$\lambda_{\text{Coherence}}$ ~ 1000 km

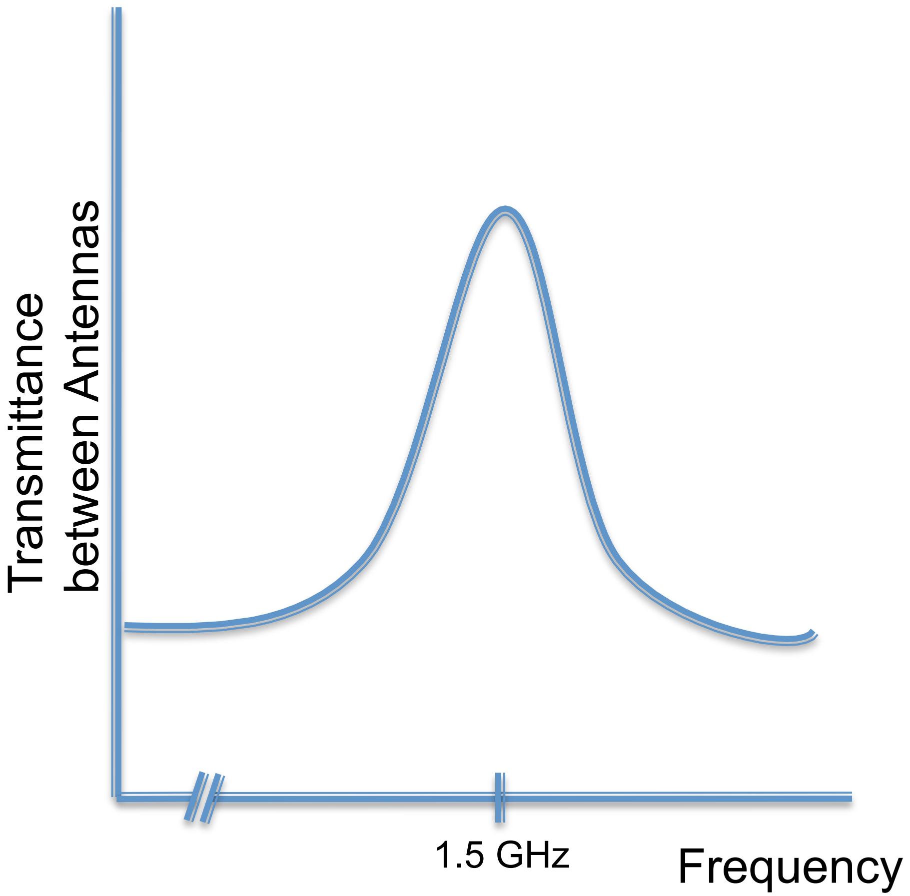
Power transfer increased by time coherence between cavity E-field and axion field



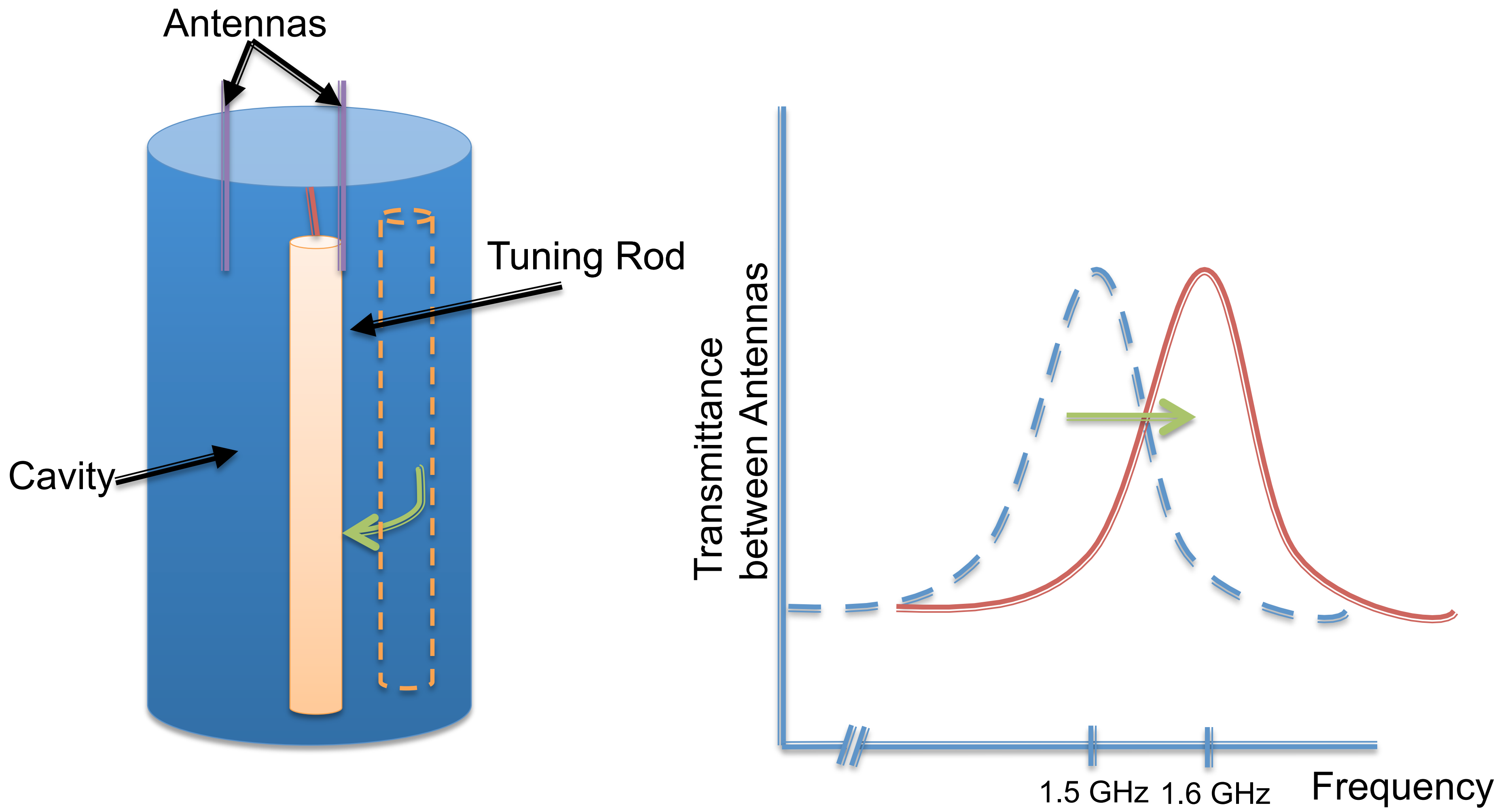
Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

Microwave Cavity needs tunable resonance



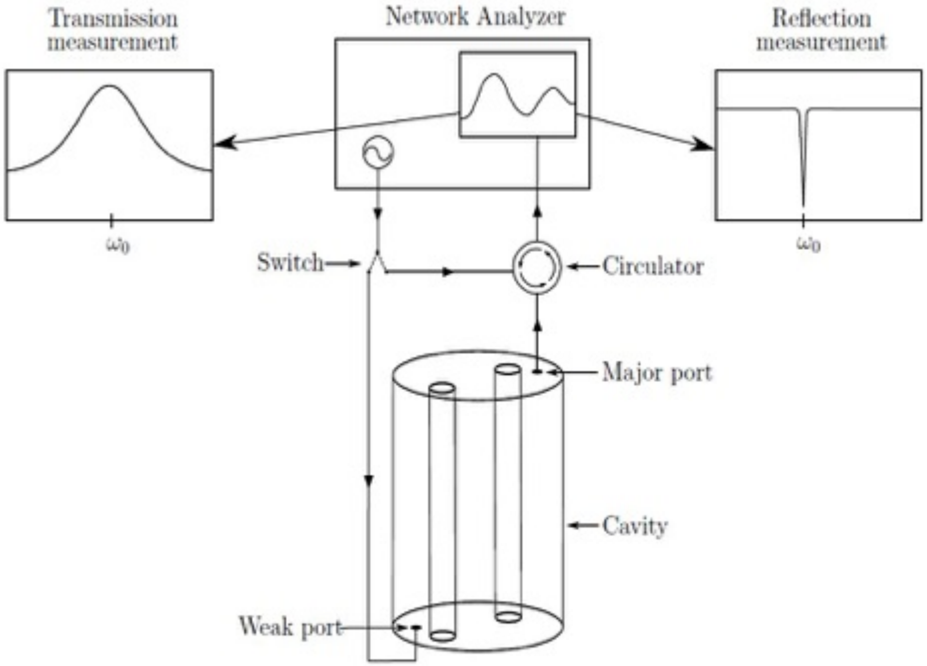


Microwave Cavity needs tunable resonance

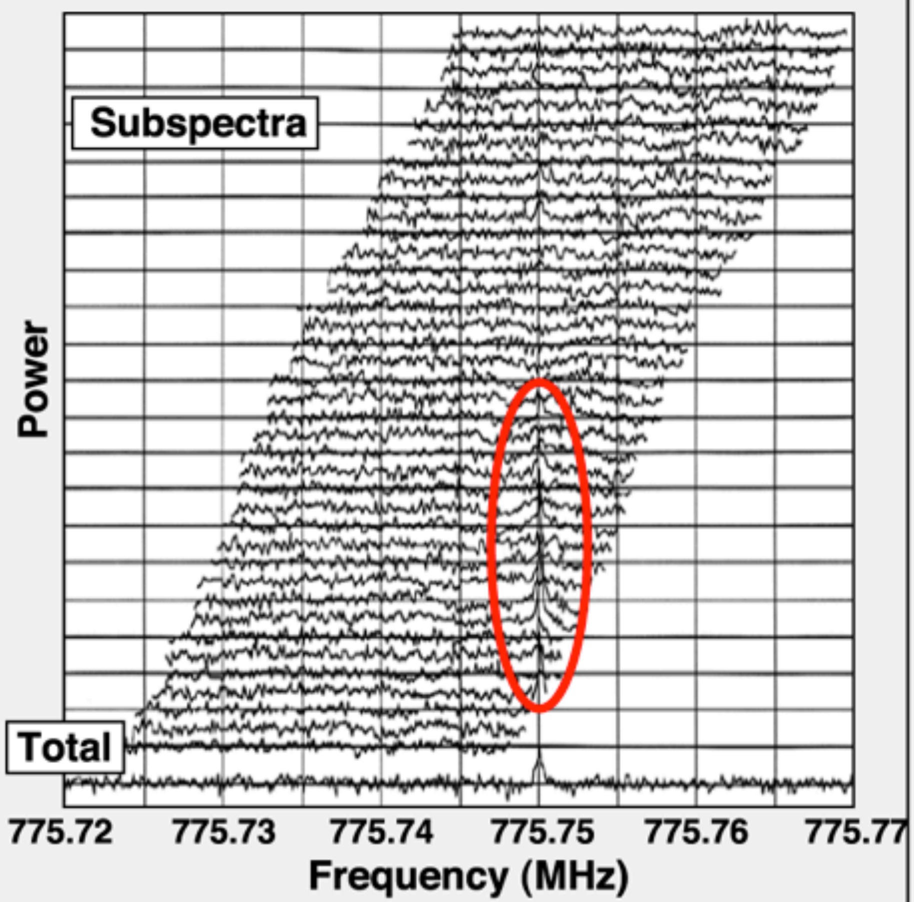
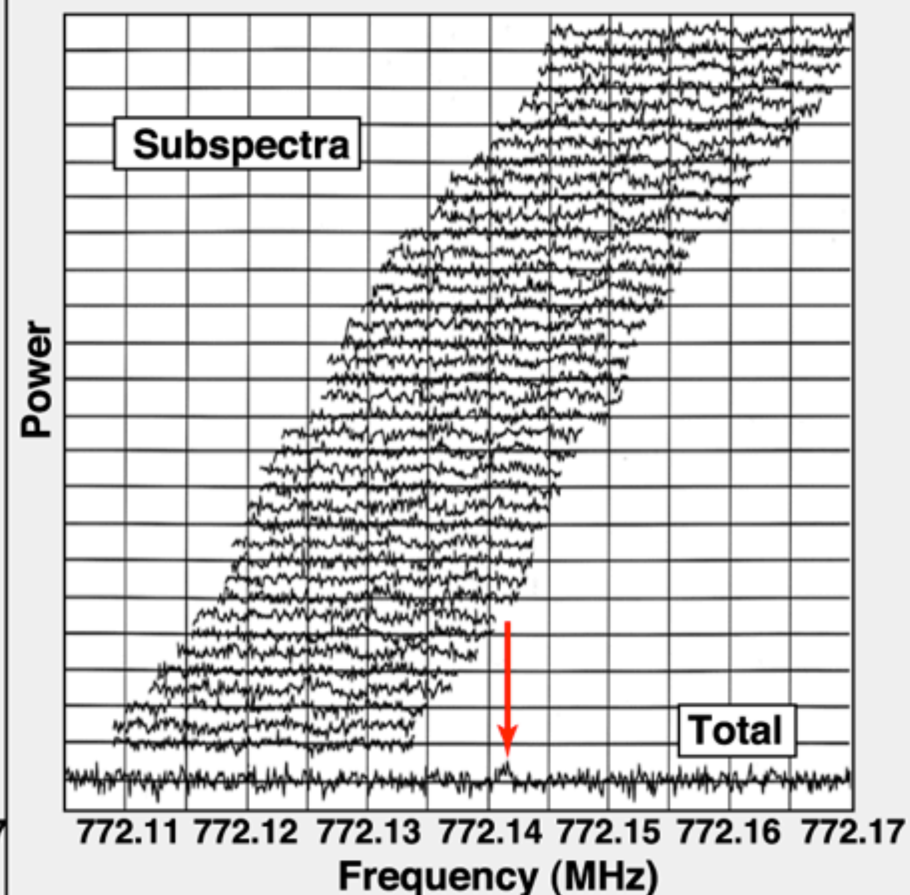


Typical ADMX Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc)
- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent experimental parameters).
- Every few days adjust the critical coupling of the antennas
- Scan rate is trade off in sensitivity vs frequency (mass) coverage
- The scan rate uses a threshold sensitivity.
- Any candidate above threshold is flagged for further study.



Sample data and candidates

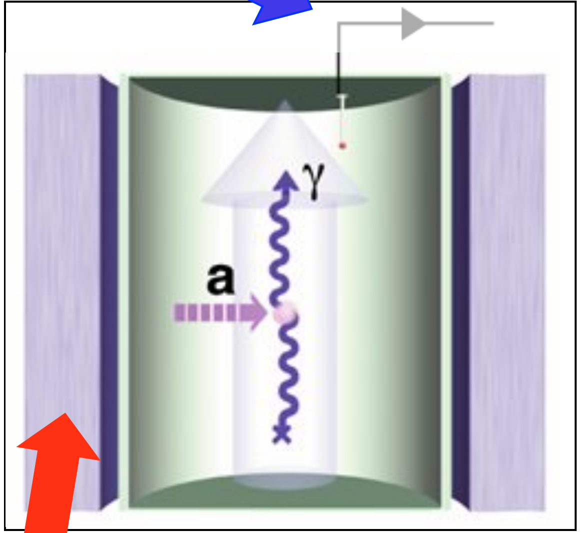
<table>
<tr><th>Environmental</th><th>Statistical</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Signal maximizes off-resonance: Radio peak</td><td>Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)</td></tr>
</table>

The Radiometer equation dictates strategy

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

But integration time limited to ~ 100 sec

* *Dicke, 1946*



System noise temp. now

$T_S = T + T_N \sim 1.5 + 1.5\ K$

But $T_{Quant} \sim 30\ mK$

This is where we invested to get to Gen 2

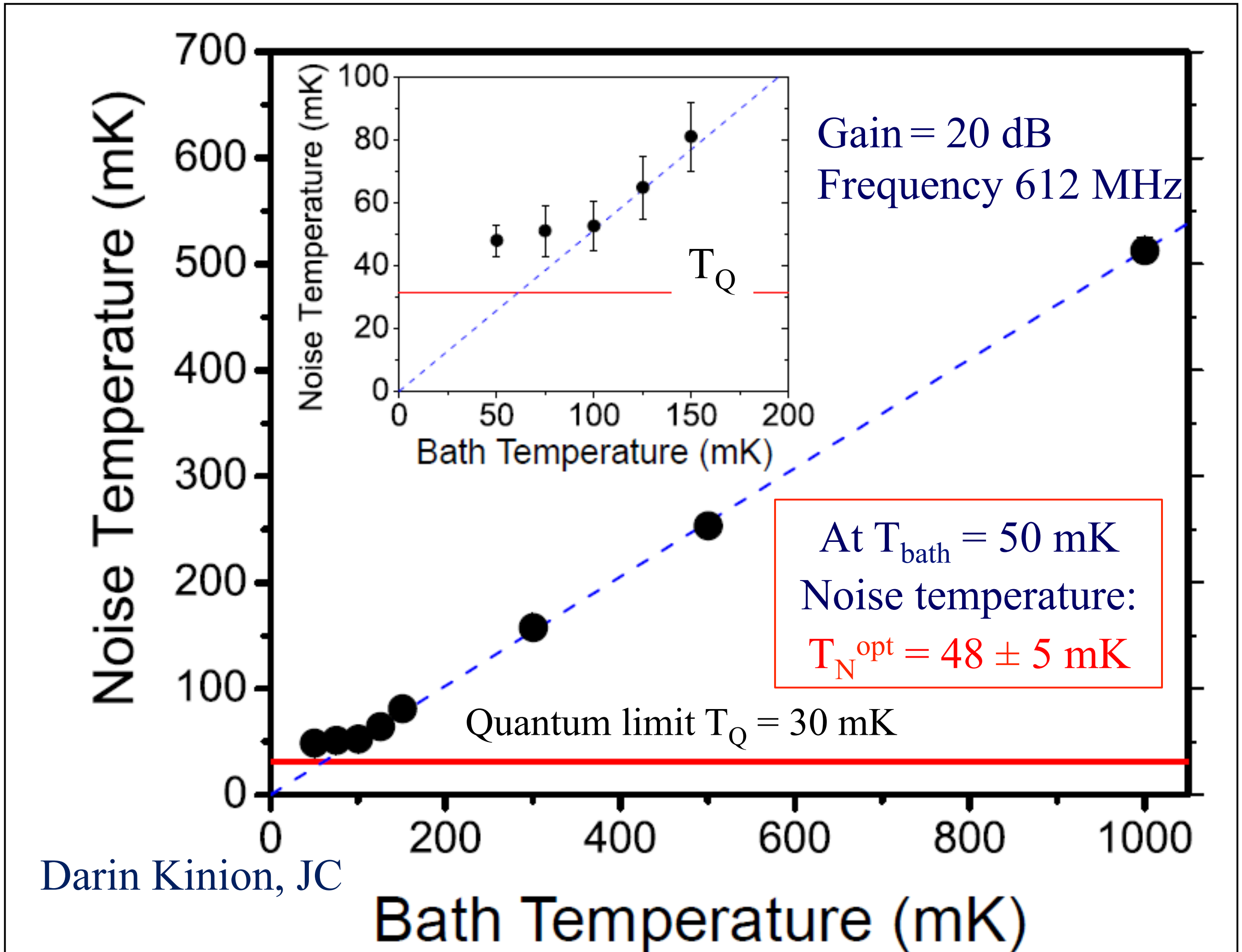
$$P_{sig} \sim (B^2V\ Q_{cav})(g^2\, m_a\, \rho_a)$$

$\sim\ 10^{-23}$ Watts for ADMX

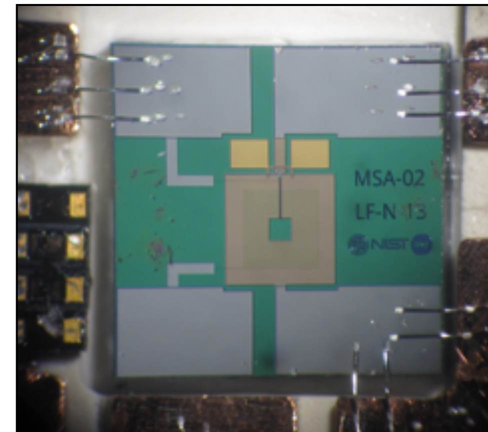
But magnet size, strength $B^2V \sim \$$

Enabling technology: Quantum-limited amplifiers

500-1000 MHz Microstrip SQUID Amp (MSA) Devices



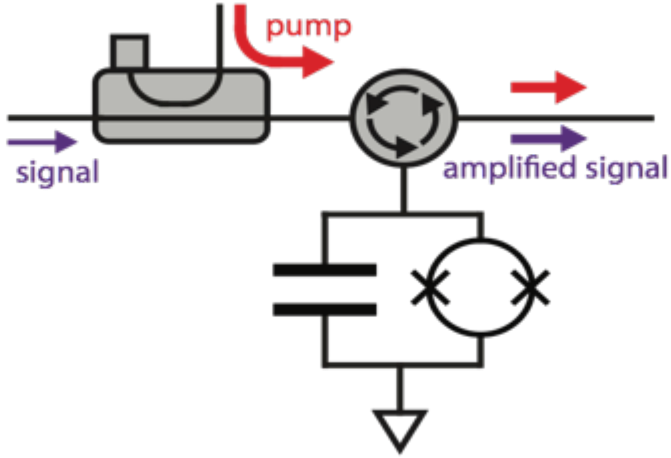
UCB produced
Prof. John Clarke

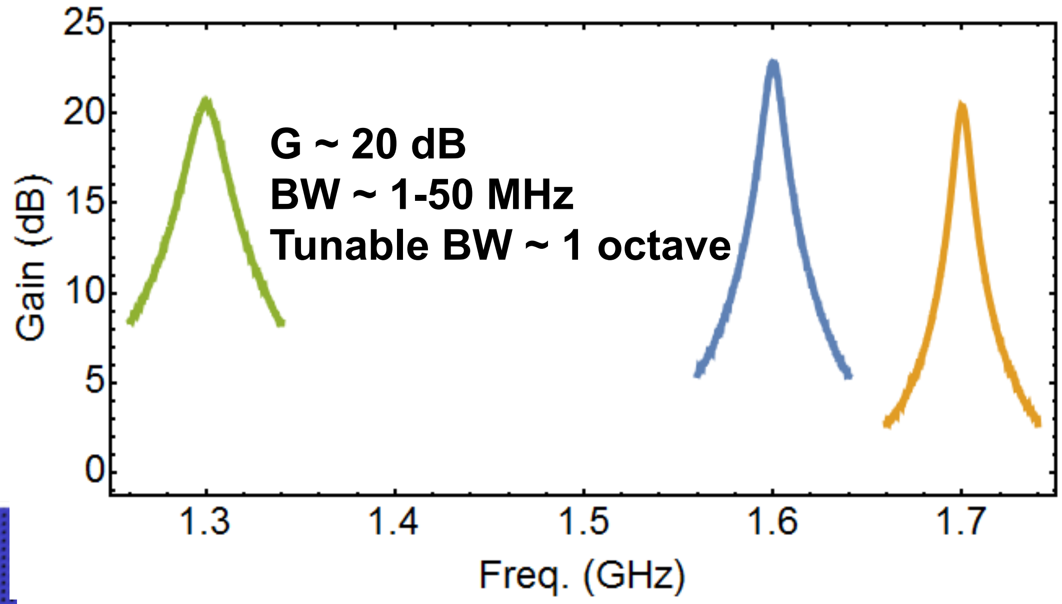


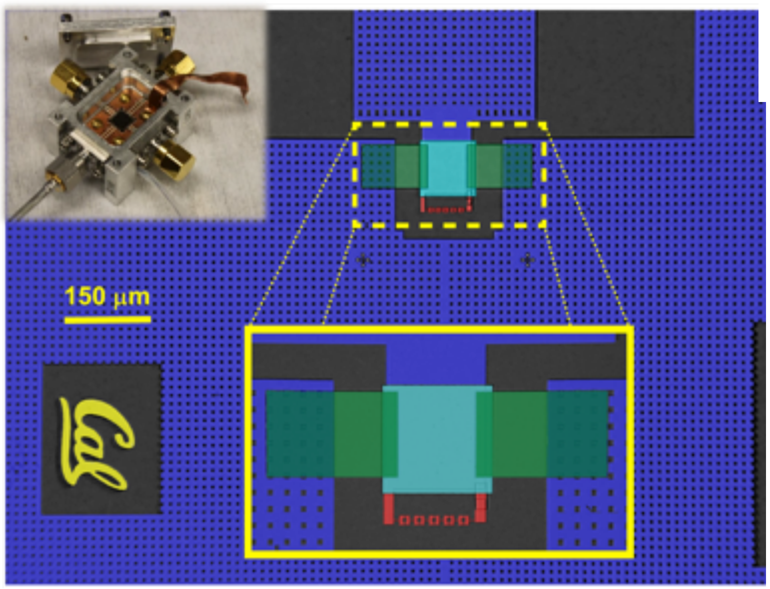
Noise temperatures of 48 ± 5 mK have been demonstrated at 612 MHz, within 1.7 times the quantum limit

Josephson Parametric Amplifier: 1-10 GHz

(UCB Design – Prof. Irfan Siddiqi)

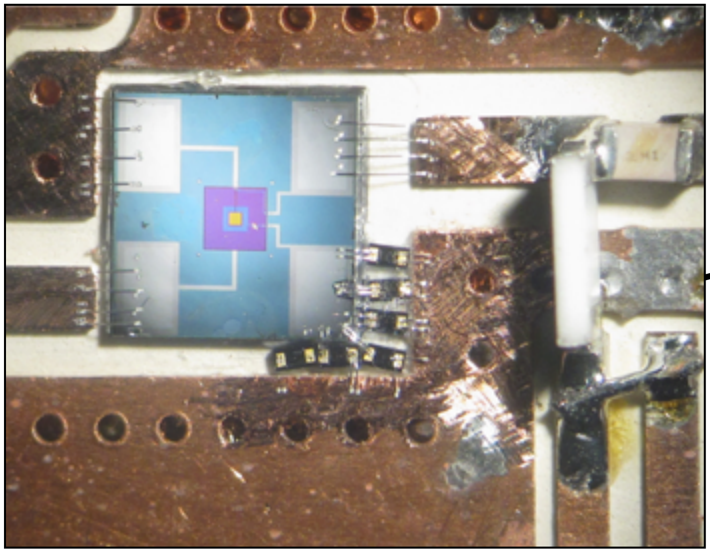




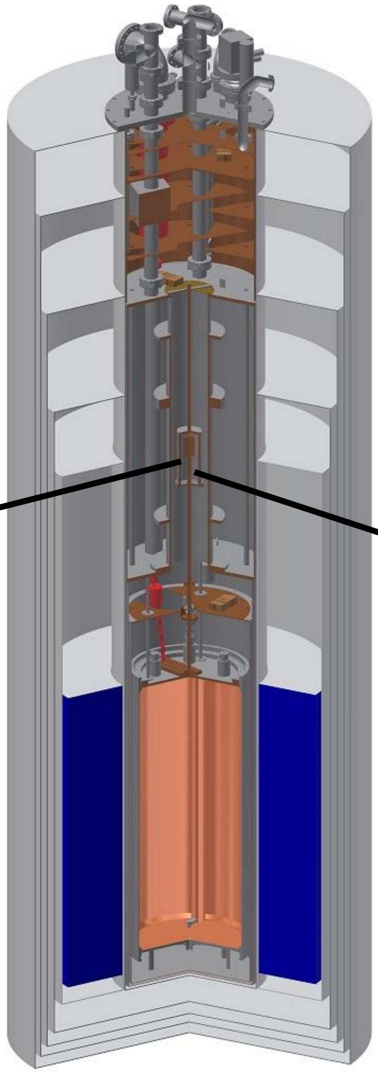


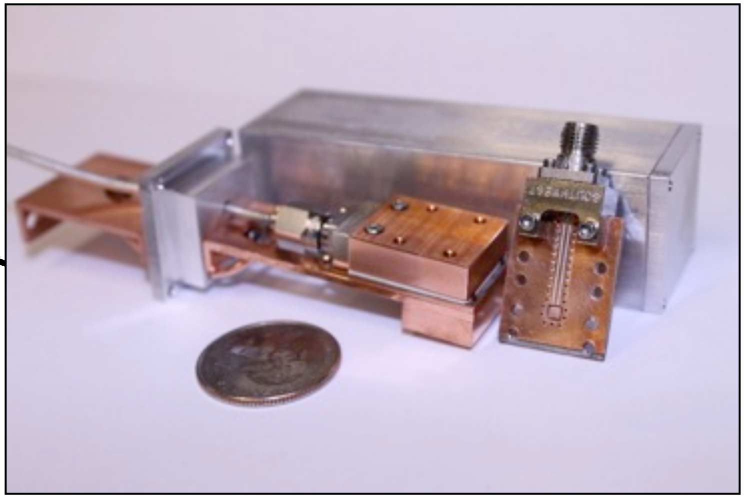
- Device recently installed in ADMX
- 2nd antenna channel (TM_{020} mode)

Quantum Limited Amplifiers



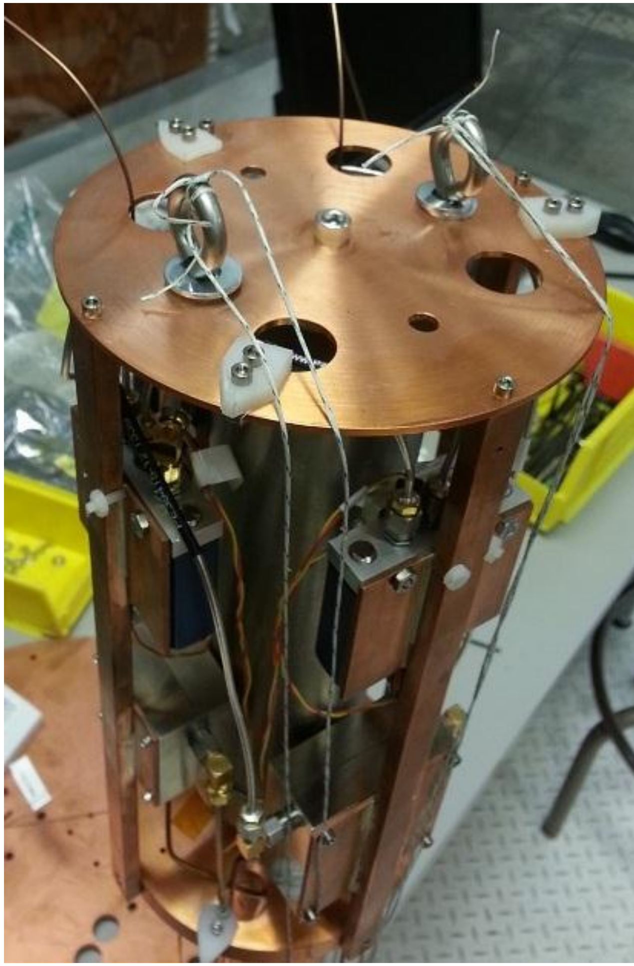
SQUIDs
(at lower frequencies)

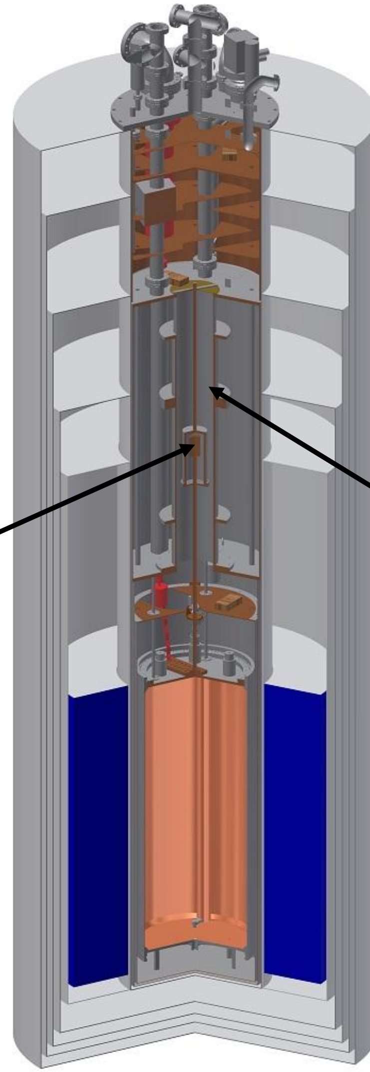


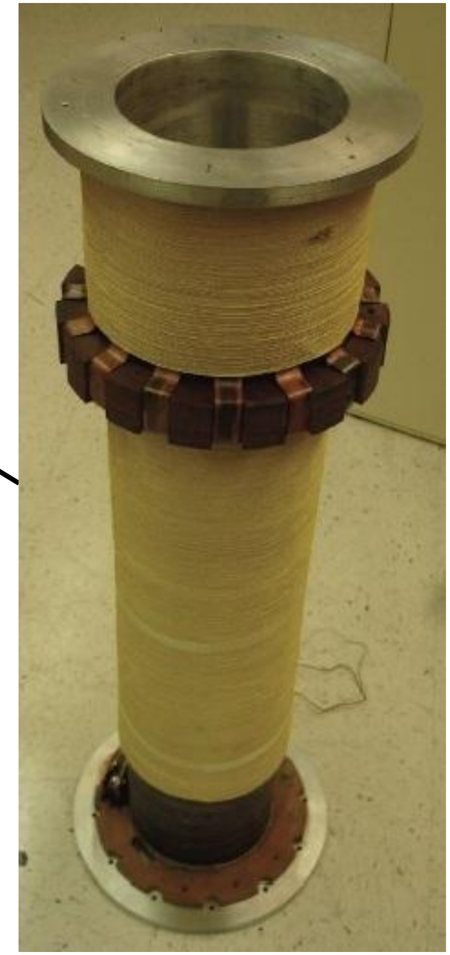


"JPAs"
(at higher frequencies)

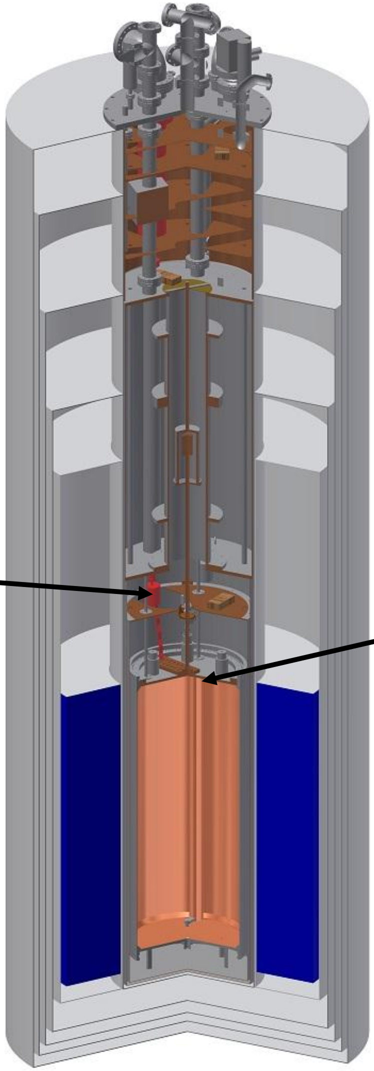
Amplifier “Squidadel” and Bucking Magnet







Cavity and thermal shielding (4 K, 1 K, 100 mK)



ADMX site: University of Washington

Center for Experimental Nuclear Physics and Astrophysics (CENPA)

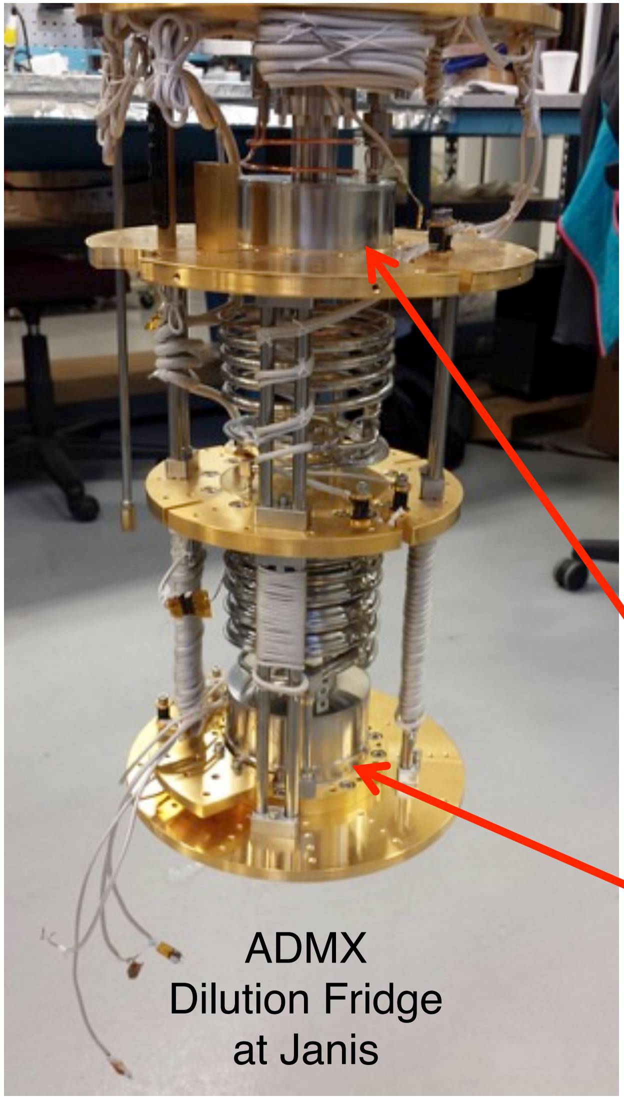
ADMX DAQ & Controls

Cleanroom
(with insert hanging)

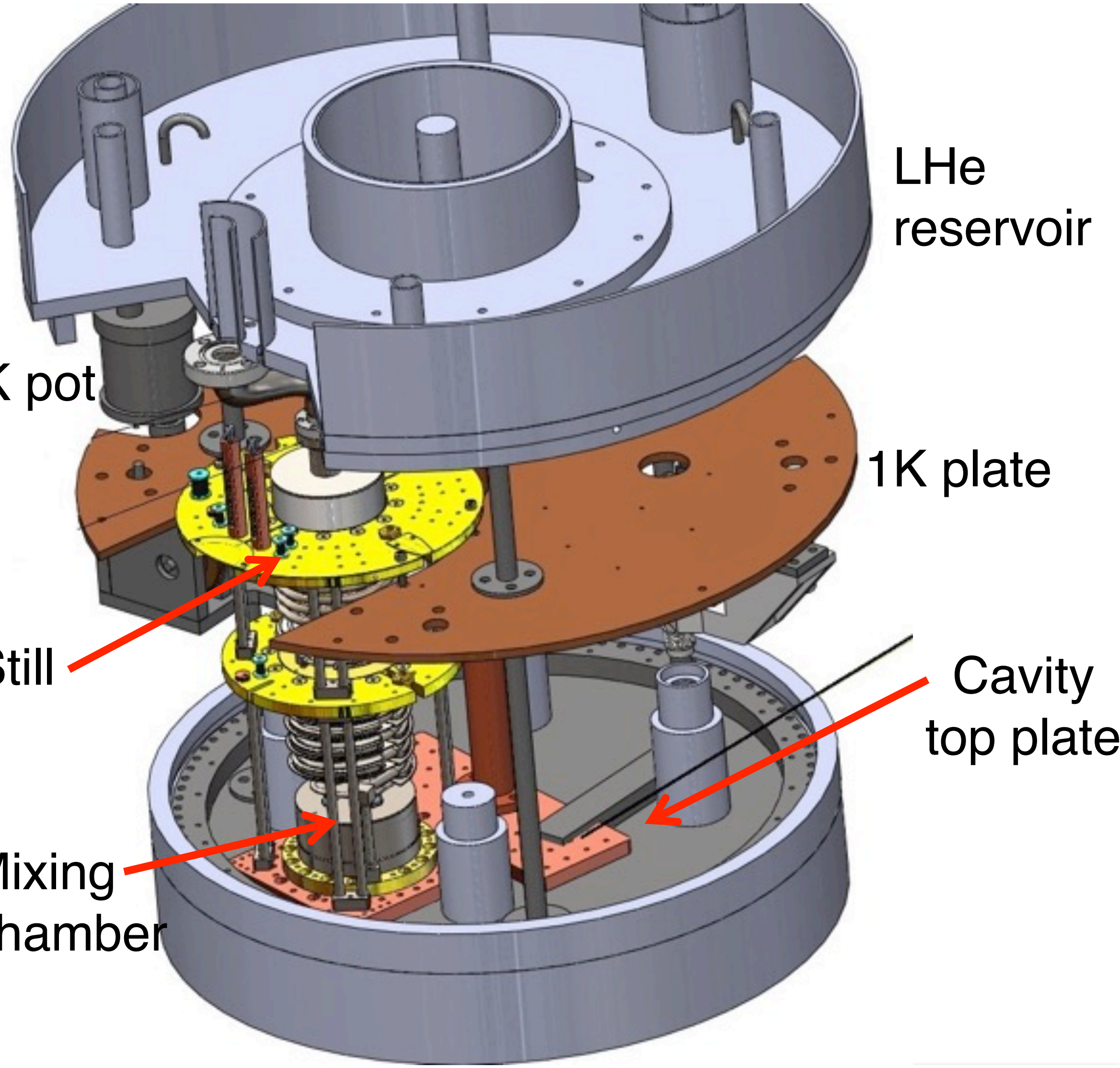
ADMX Magnet

Helium liquefier

Dilution Refrigerator (800 μW at 100 mK)
Cold stage directly on cavity



ADMX
Dilution Fridge
at Janis

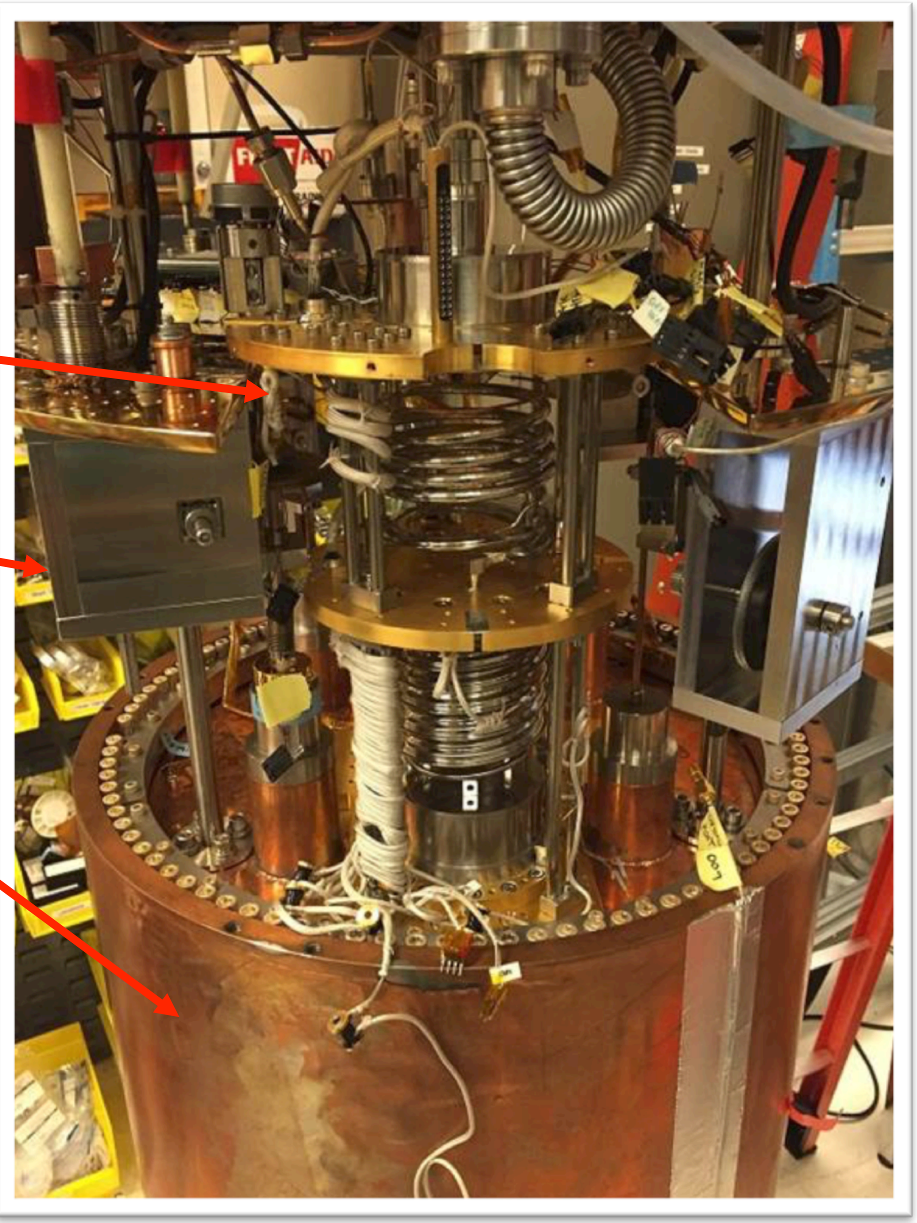


Dilution Refrigerator: After installation onto cavity

Dilution refrigerator

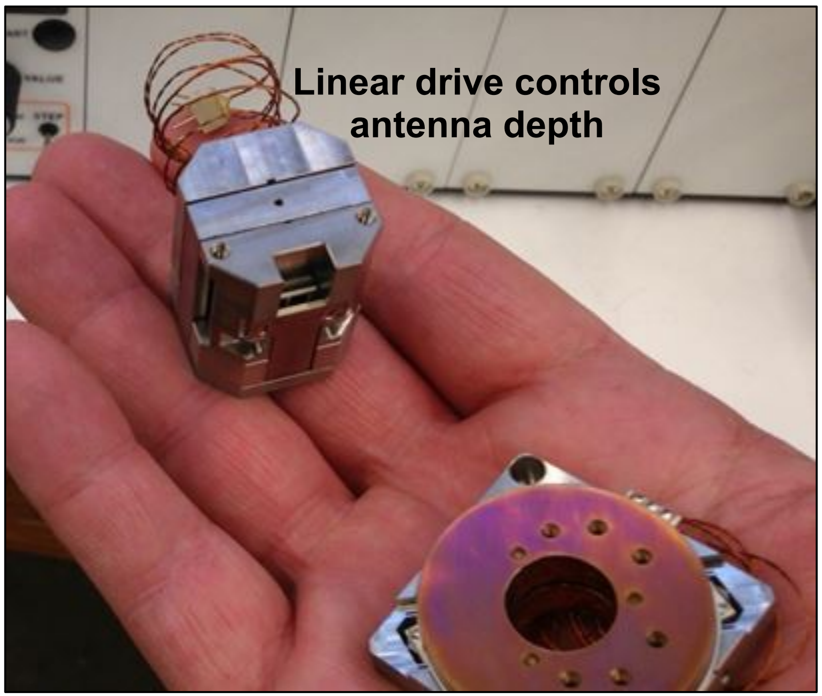
Rotary Gearboxes

Main Cavity



2nd cavity system: Sidecar (4 – 6 GHz)

- Test new technologies **<u>in-situ</u>** and search in new frequency ranges (4-6 GHz) (piezoelectric motors, JPAs, etc)
- Mounted directly above main cavity
- Piezos to replace large bulky gearboxes



Rotary drive controls tuning rod

Piezos compatible with high B-field (>30 T), vacuum and cryogenic temperatures (10 mK)

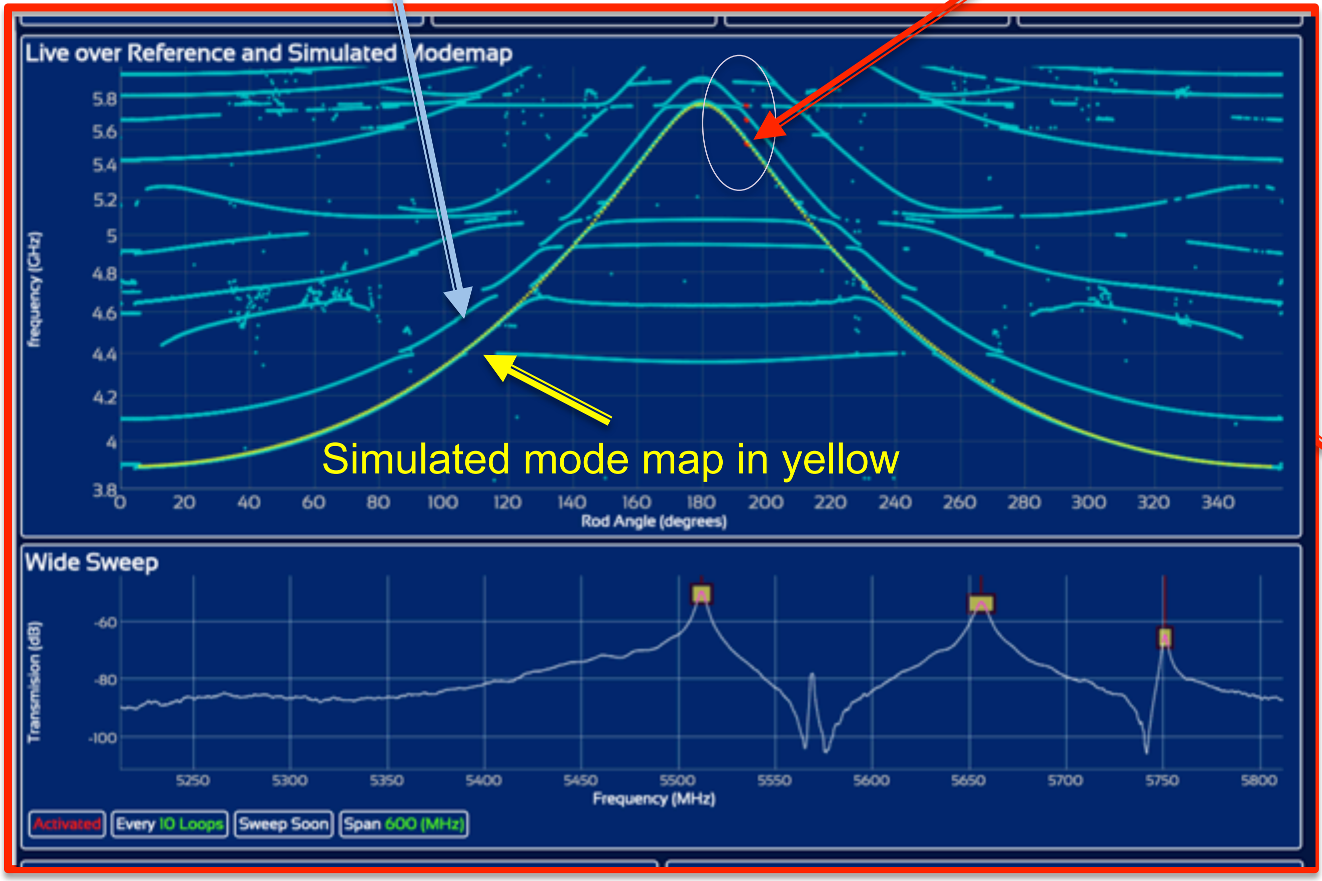
Recent ADMX cold commissioning run

- June install followed by systems tests
- Long, slow initial cool down to monitor for any 3He/4He leaks in the dilution refrigerator (2 months).
- Subsequent cool downs ~ 3 weeks.
- Magnet ramp, 9 Aug to 2 Tesla
- Later brought to 5.5 Tesla (full field is 7.5 Tesla)
    - No evidence of vibration heating from motion in field ✓
    - No evidence of cavity heating from motion control ✓

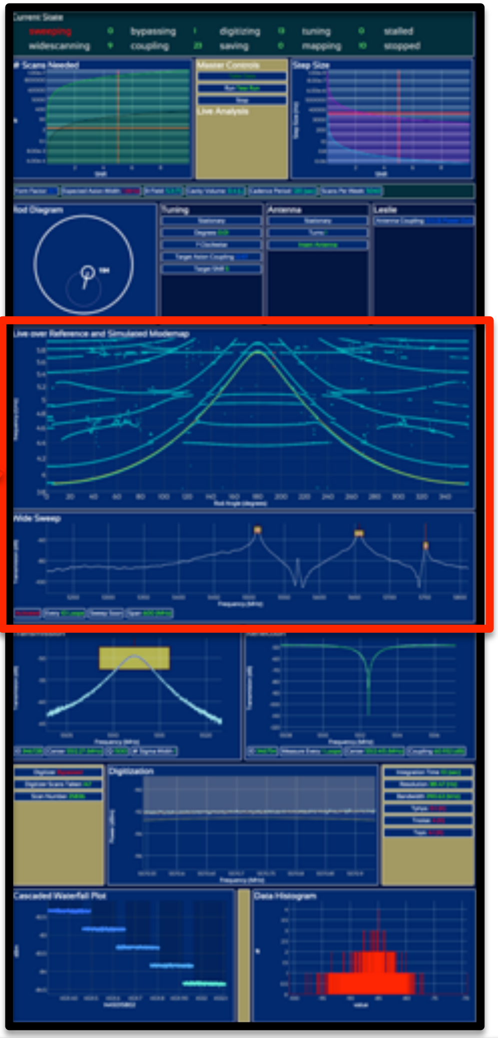
Sidecar DAQ: Frequency Mode Map

Reference mode map in blue

Red Dots are live data taken from wide scan

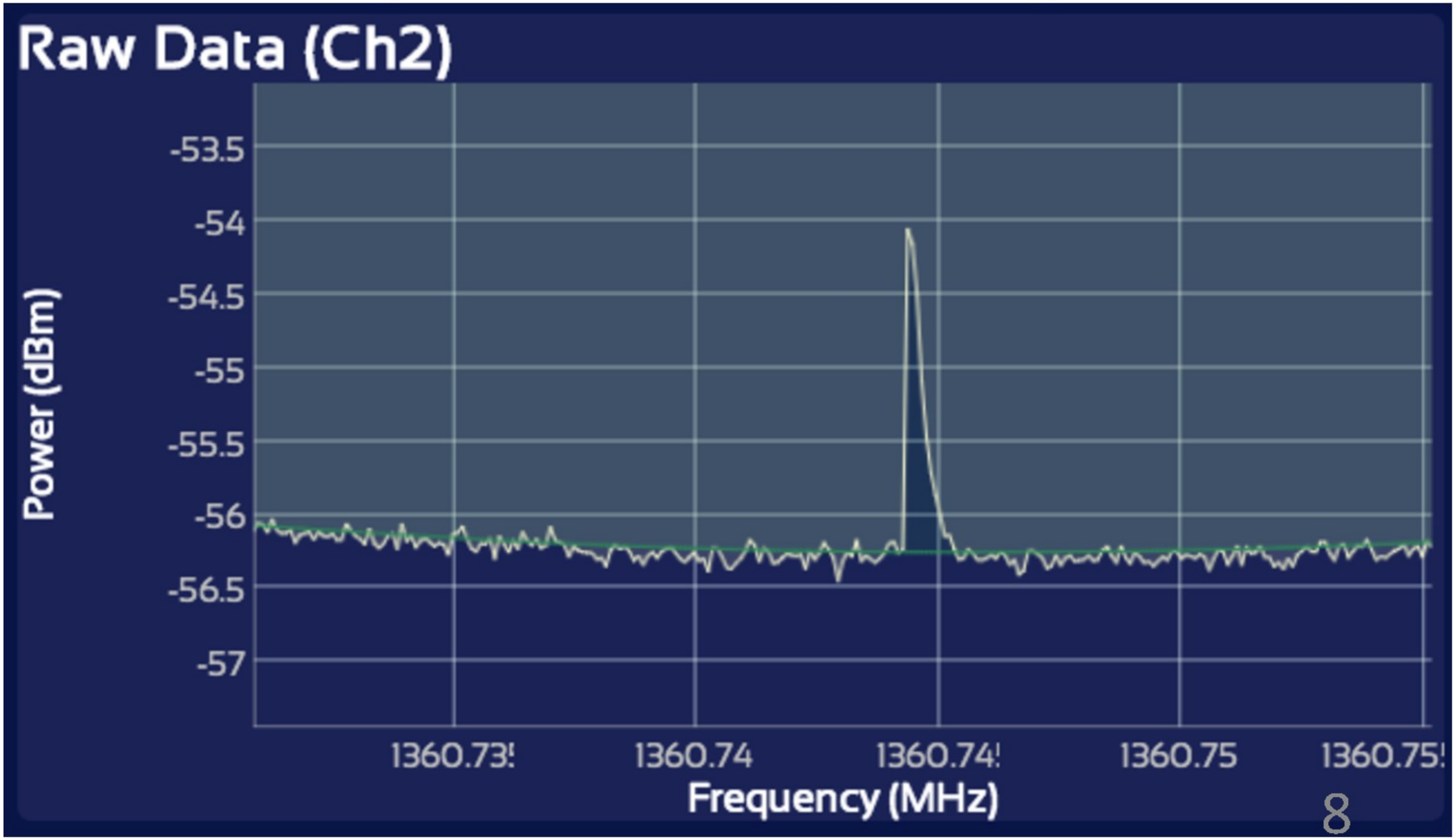


Simulated mode map in yellow



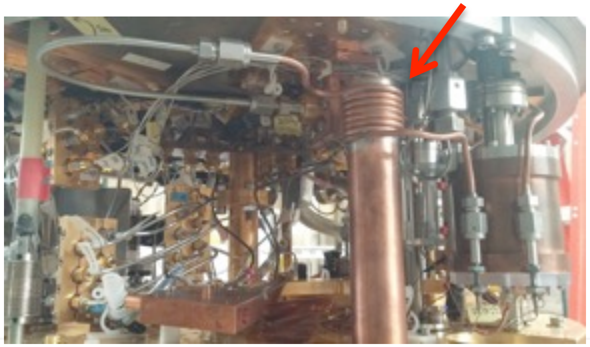
Raw data and hardware synthetic axion (×100)

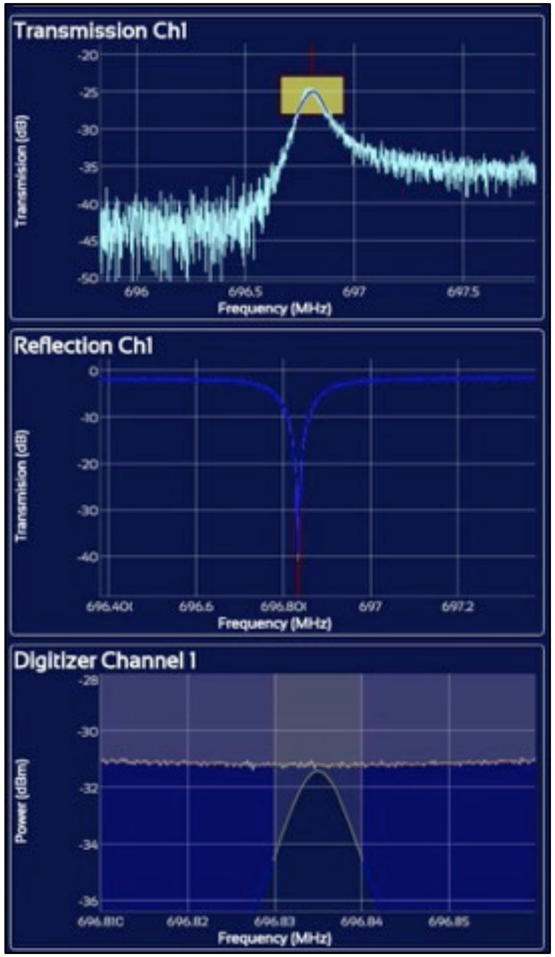
Able to inject custom lineshape through weak port (blinded)



ADMX recent commissioning run

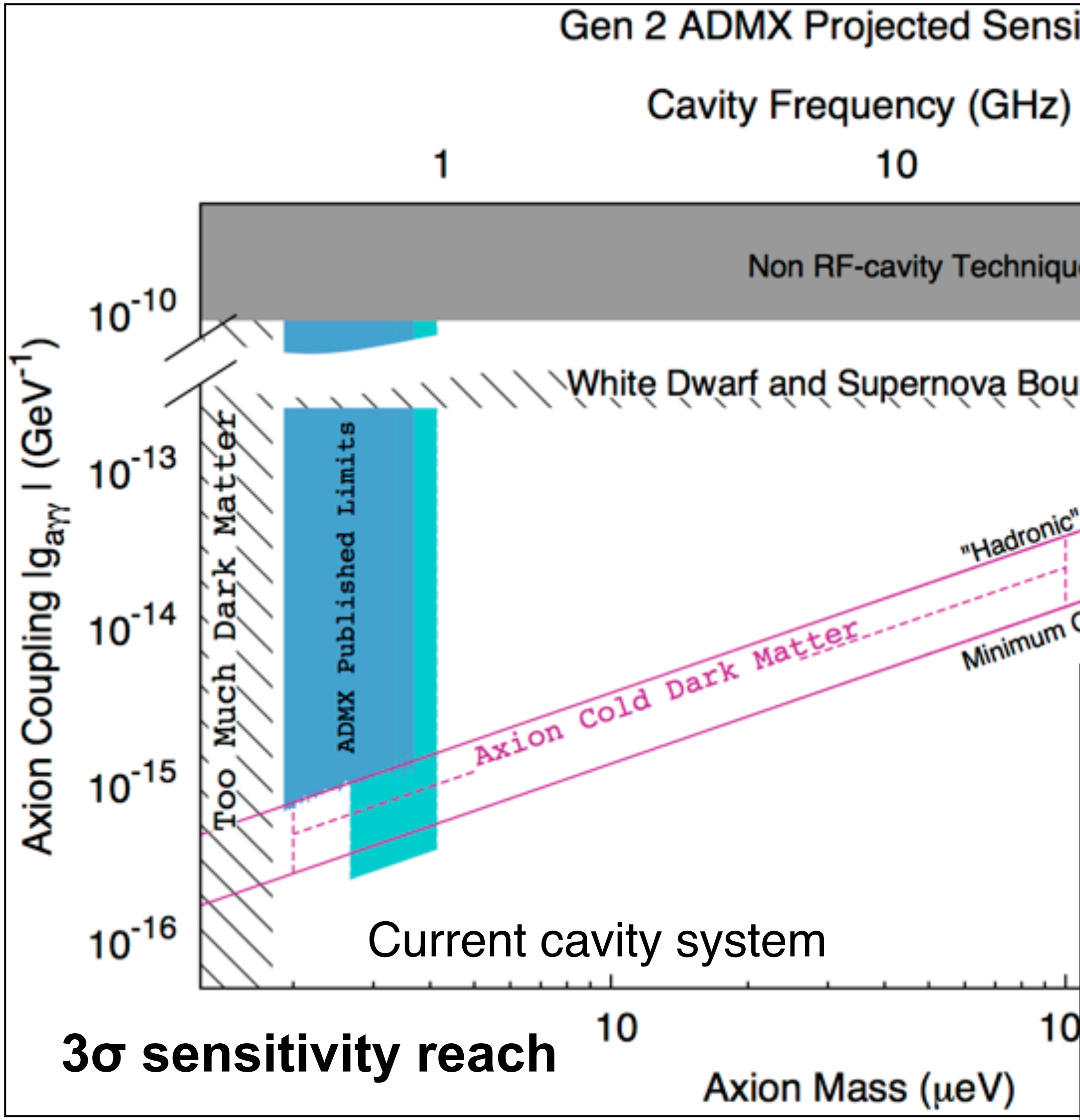
- **Took data from Aug 9th – Oct 3rd**
- **Dilution refrigerator maintained stable operations @ 200 mK**
  - Not at design temp yet... design goal <150 mK.
  - Testing before pullout indicates incoming 3He/4He mixture in dilution refrigerator too hot... overpowers 1K pot
- **Took data with SQUID amp ~ 700 MHz (2.85 μeV)**
- **Sidecar cavity took data ~ 5.5 GHz (22 μeV)**
- **In the process of making minor adjustments before science data operations ← reinstall next few weeks**
  - **Fixed a few mechanical & RF disconnects**
  - **Additional heat sinking of dil fridge gas mixture**



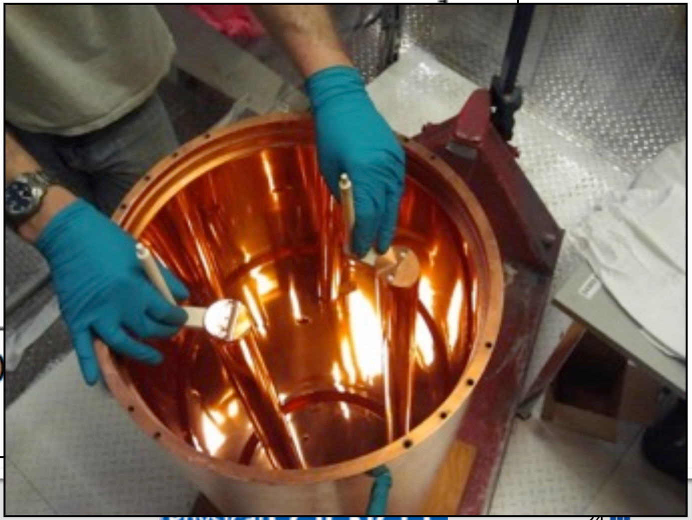
Ch1 DAQ

ADMX Science Prospects: Year 1 (0.6 – 1 GHz)

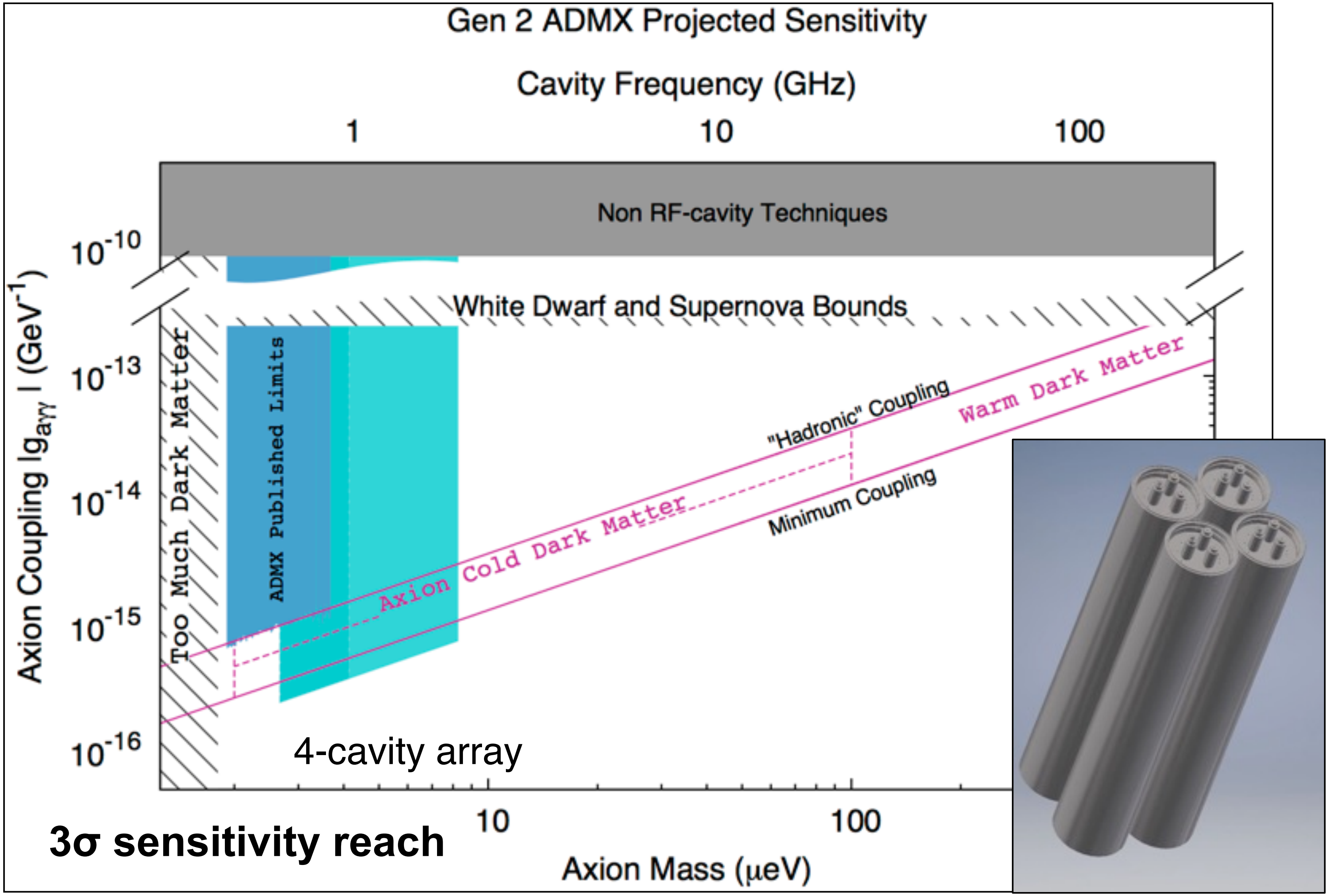


Current cavity system

3σ sensitivity reach

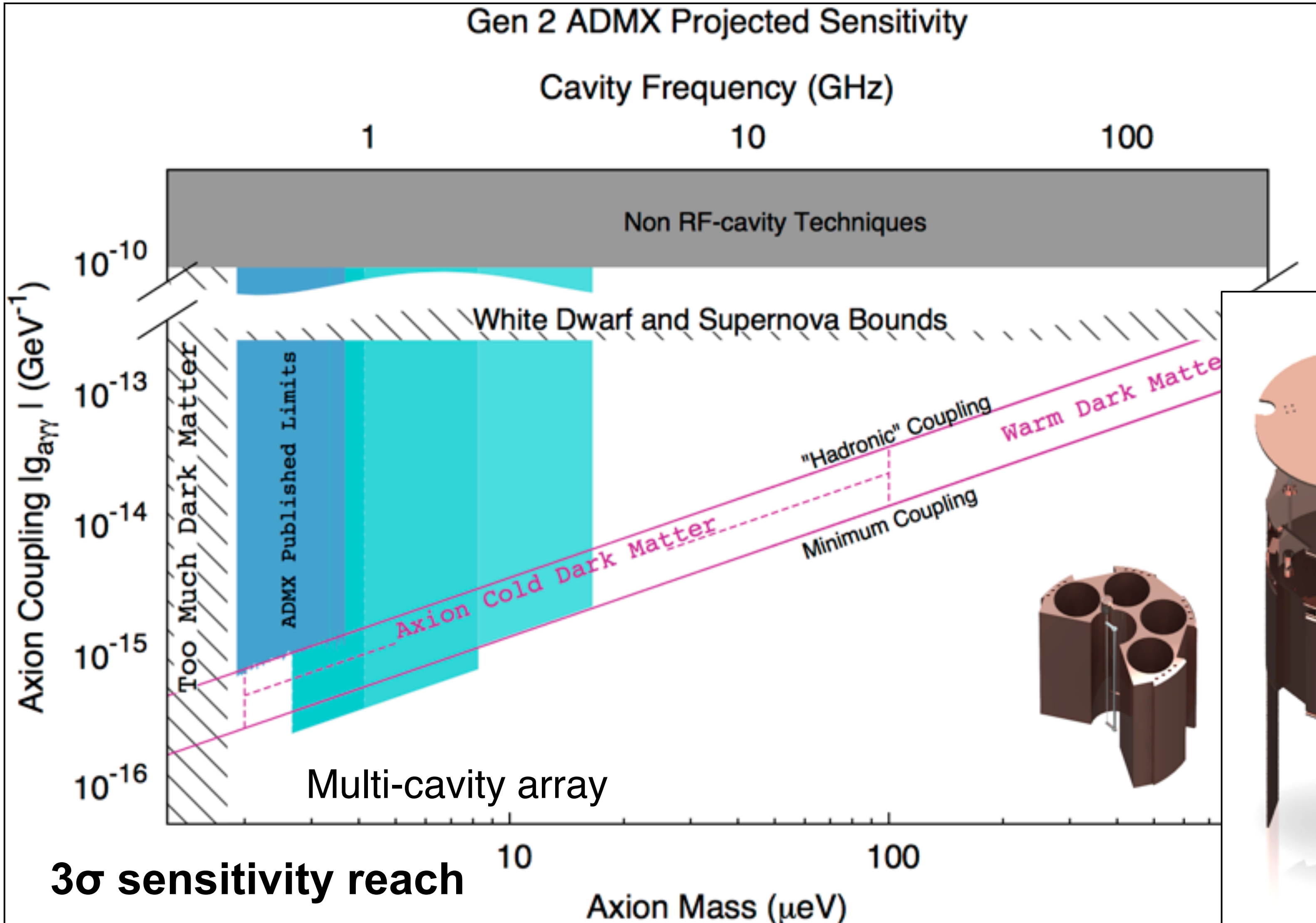


ADMX Science Prospects: Year 2 (1 – 2 GHz)

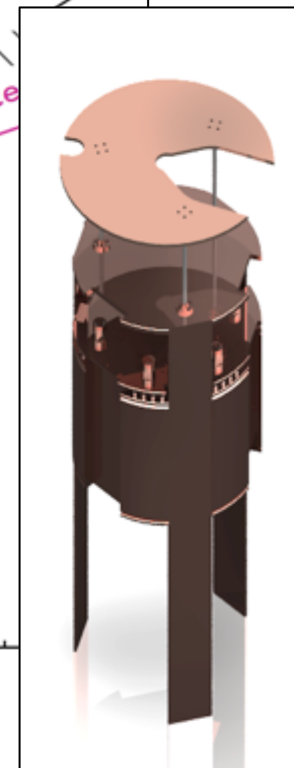


3σ sensitivity reach

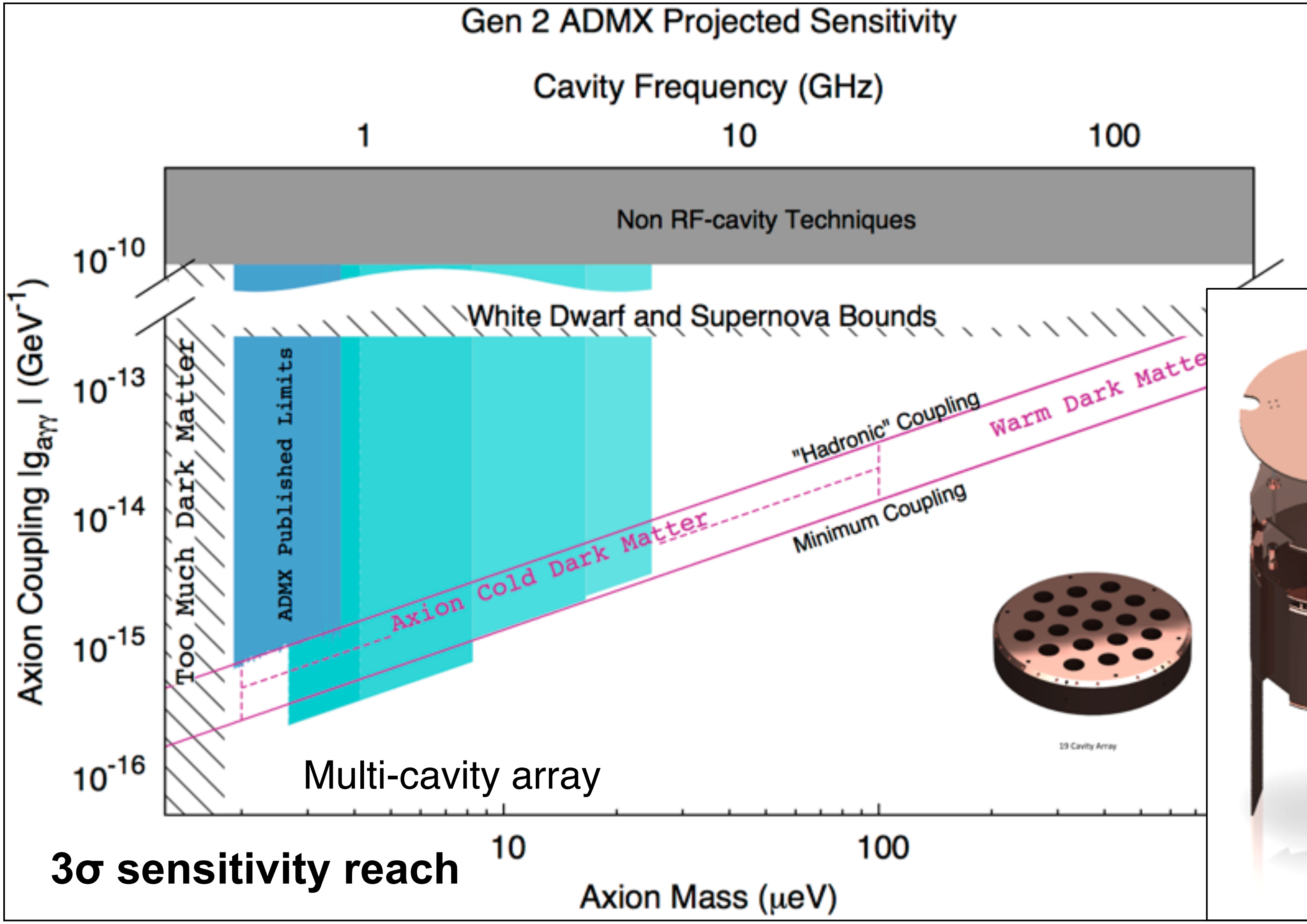
ADMX Science Prospects: Year 3 (2 – 4 GHz)

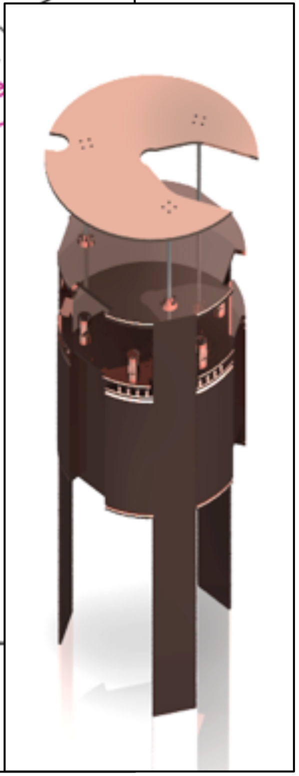


3σ sensitivity reach



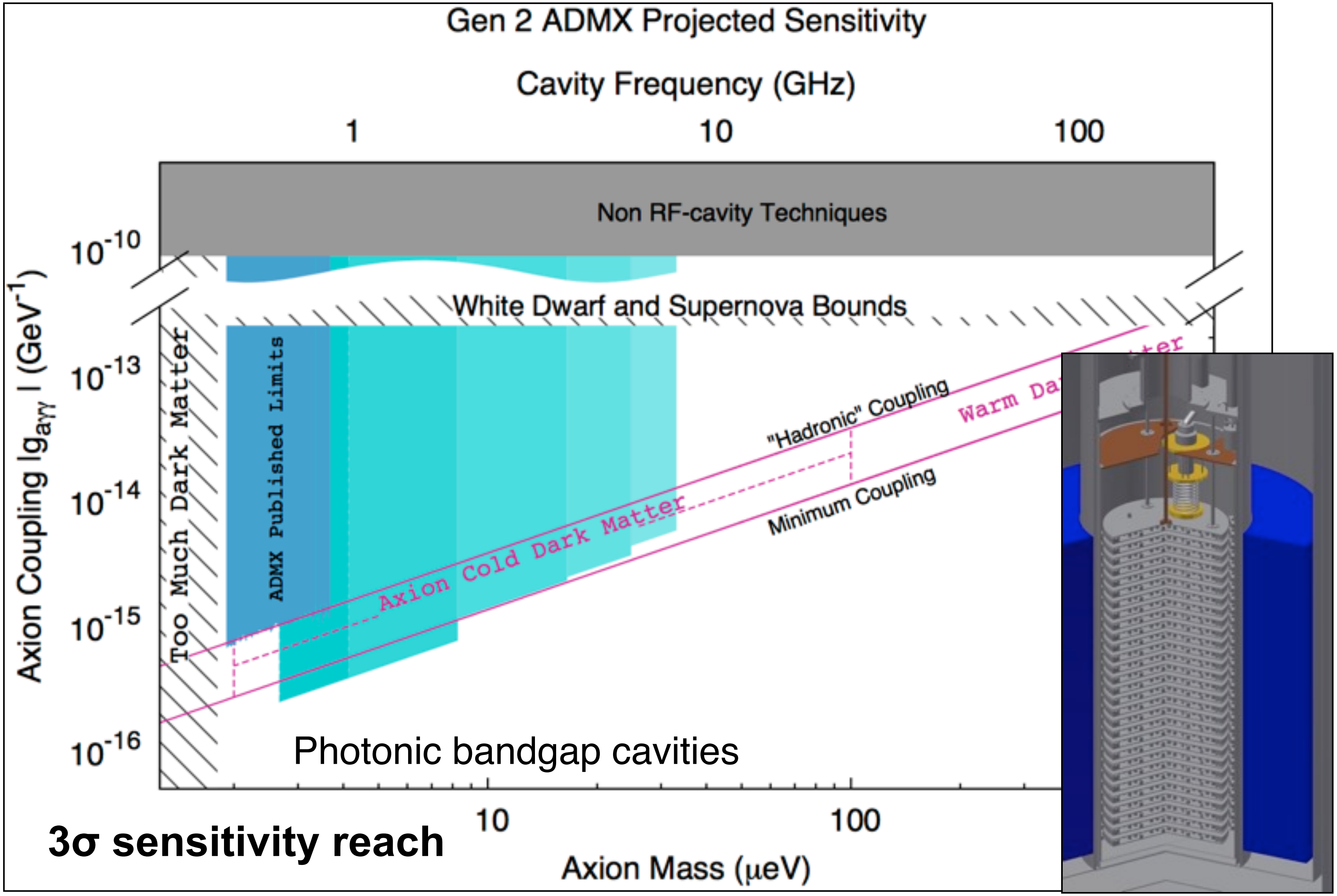
ADMX Science Prospects: Year 4 (4 – 6 GHz)





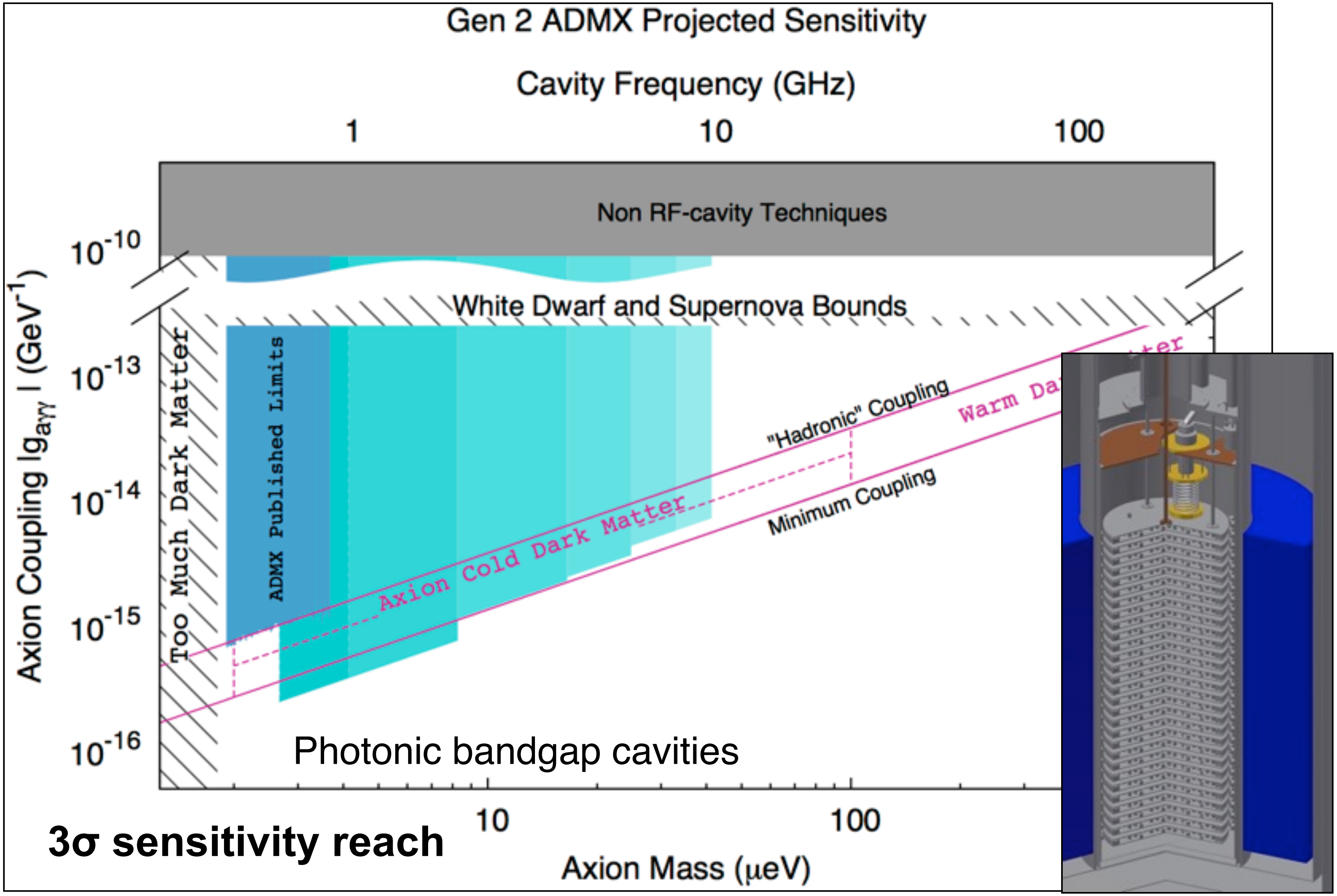
3σ sensitivity reach

ADMX Science Prospects: Year 5 (6 – 8 GHz)

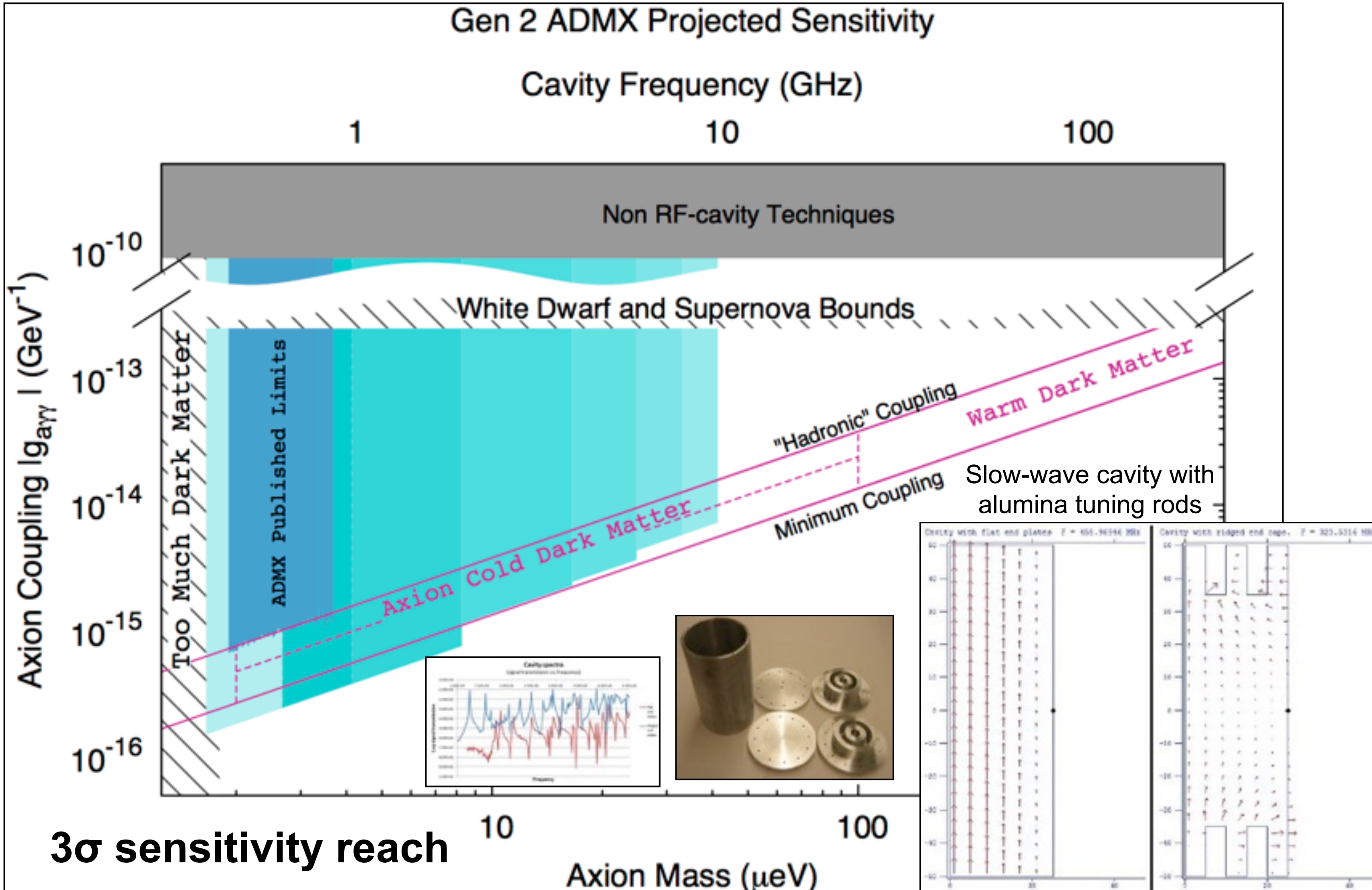


3σ sensitivity reach

ADMX Science Prospects: Year 6 (8 – 10 GHz)

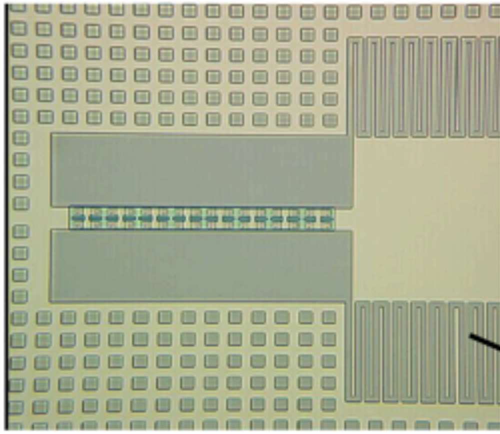


ADMX Science Prospects: Out-Years < 0.5 GHz

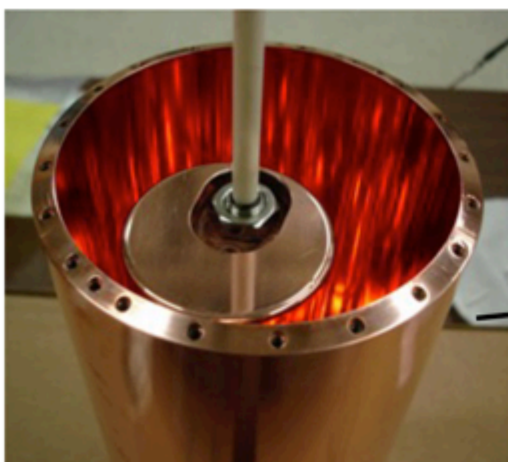


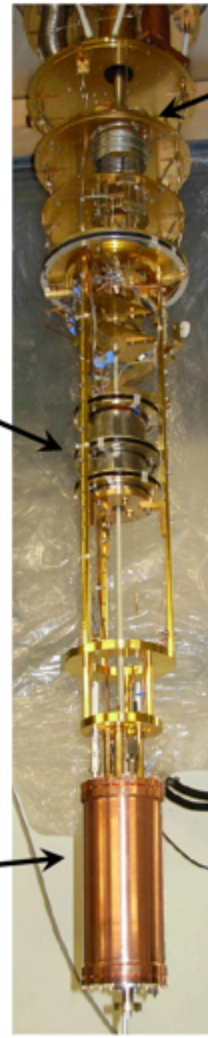
Other groups: ADMX-High Frequency
Separate collaboration sited at Yale U.

Josephson Parametric Amplifier

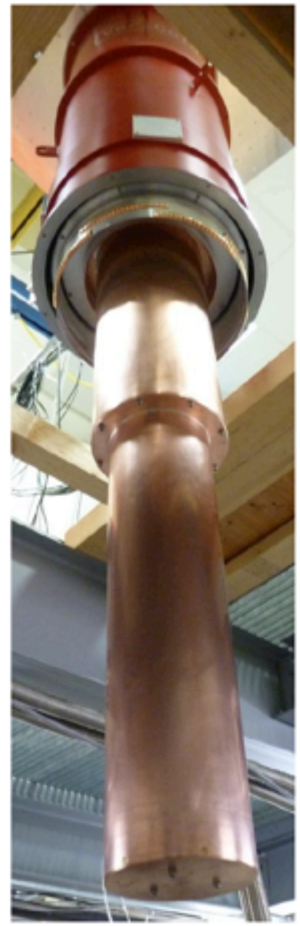


Microwave Cavity (copper)



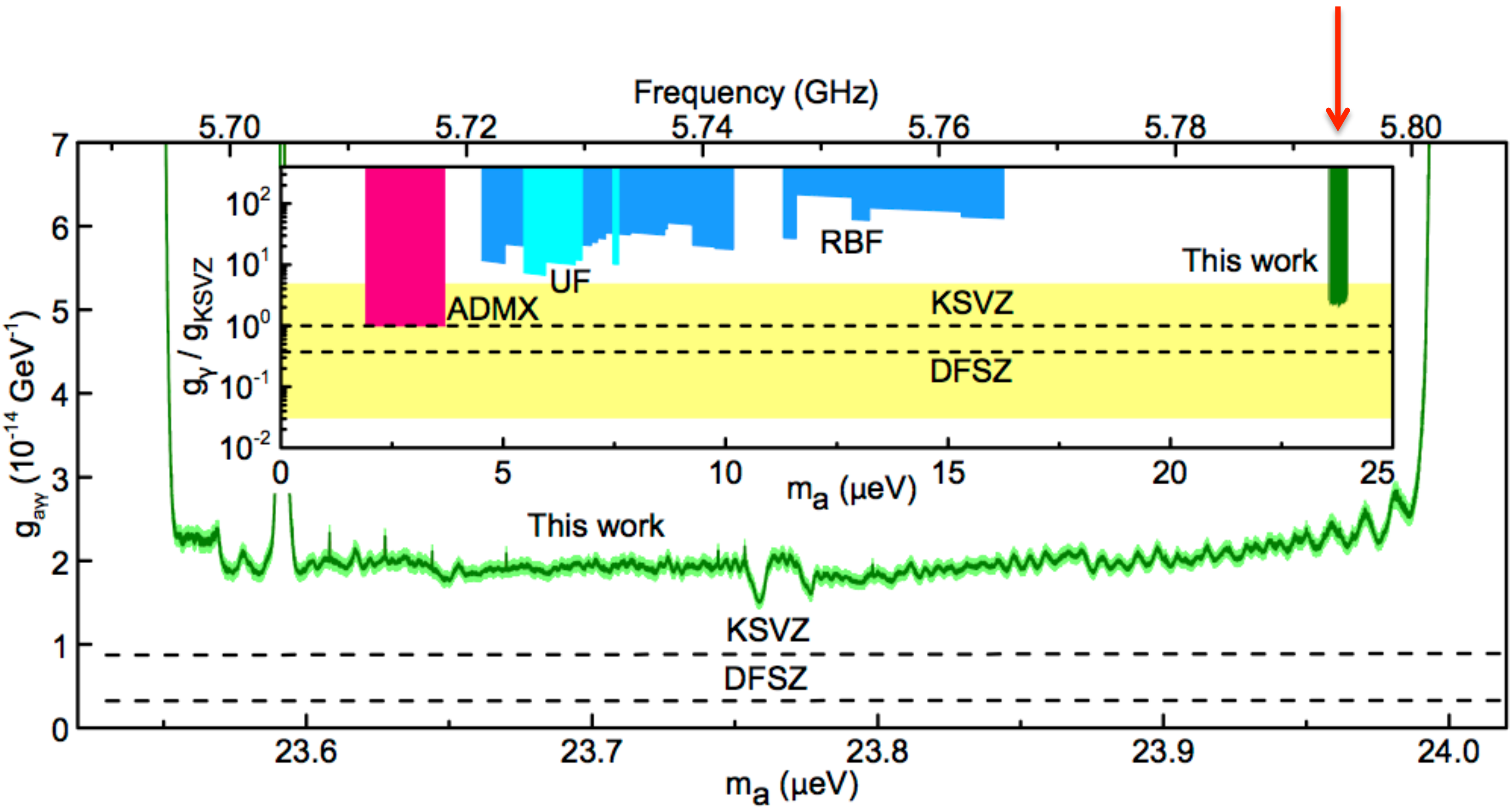


$^3He/^4He$ Dilution Refrigerator



9.4 Tesla, 10 Liter Magnet

ADMX-High Frequency: Recent data run



Recently submitted to PRL (arXiv:1610.02580)

Going beyond 10 GHz (40 μeV)…

New Magnet Systems: Maximize B^2V

- Magnet technology continues to improve
- Large solenoid fields (> 22 T) now possible
- Scan Rate ~ B^4V^2
- Prudent to invest here to broaden search
- Multiple frequencies scanned at same time

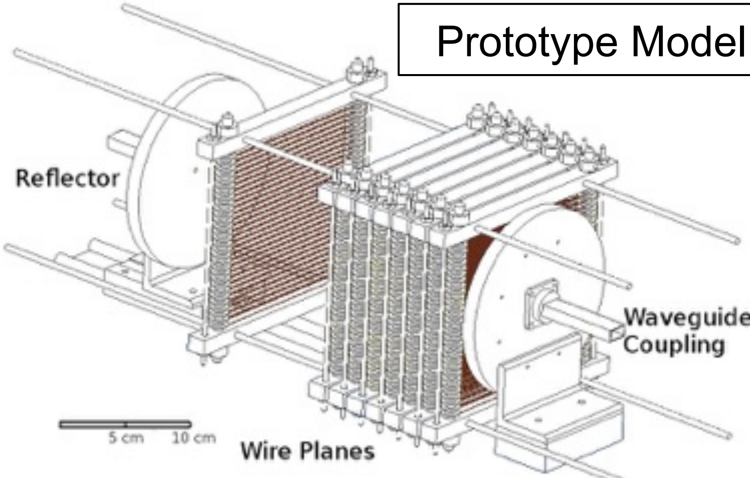
Bruker NMR magnet
23.5 T with 5.4 cm bore

ADMX magnet
8 T with 0.5 m bore

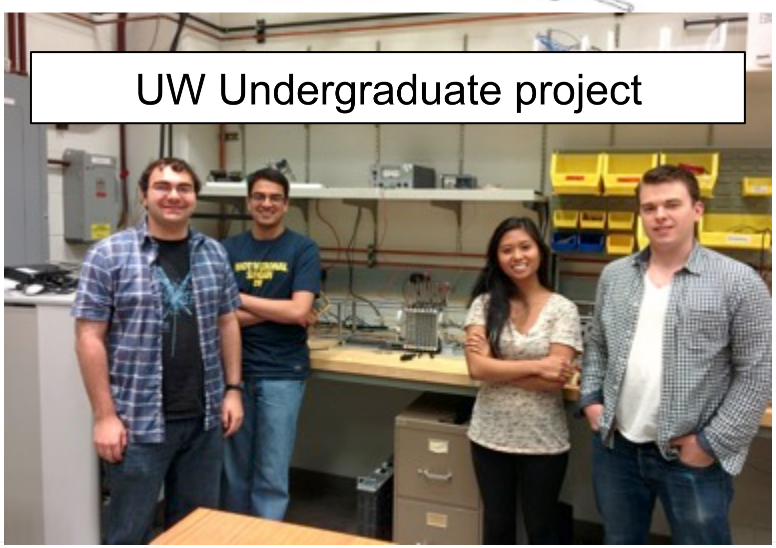
New Geometries: Open Resonator R&D

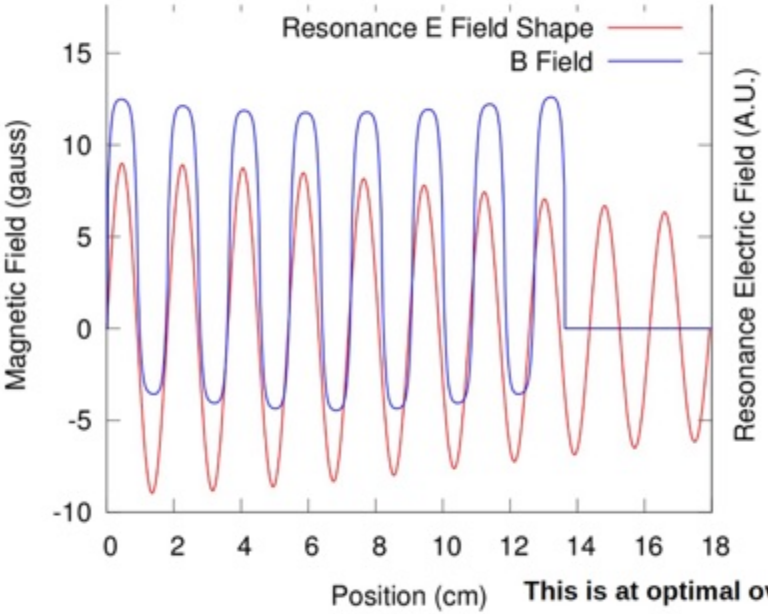
Open resonators may access frequencies too high to reach with closed cavities could expand ADMX reach to highest possible dark matter axion masses

Prototype Model



UW Undergraduate project





This is at optimal overlap

PhysRevD.91.011701

System potentially good to much higher frequencies (40 GHz or more)

Open Resonator R&D

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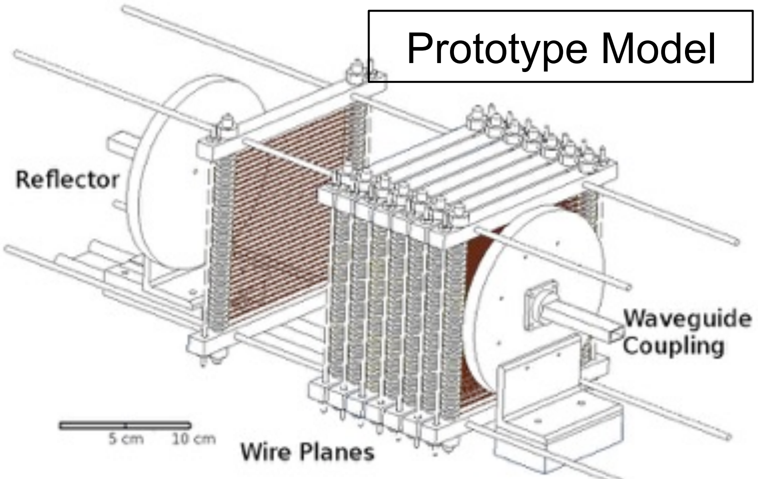
Prototype Model



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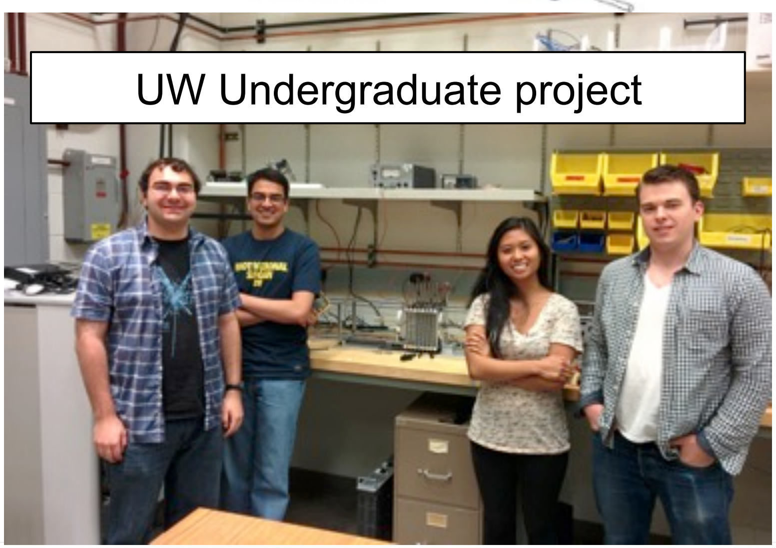

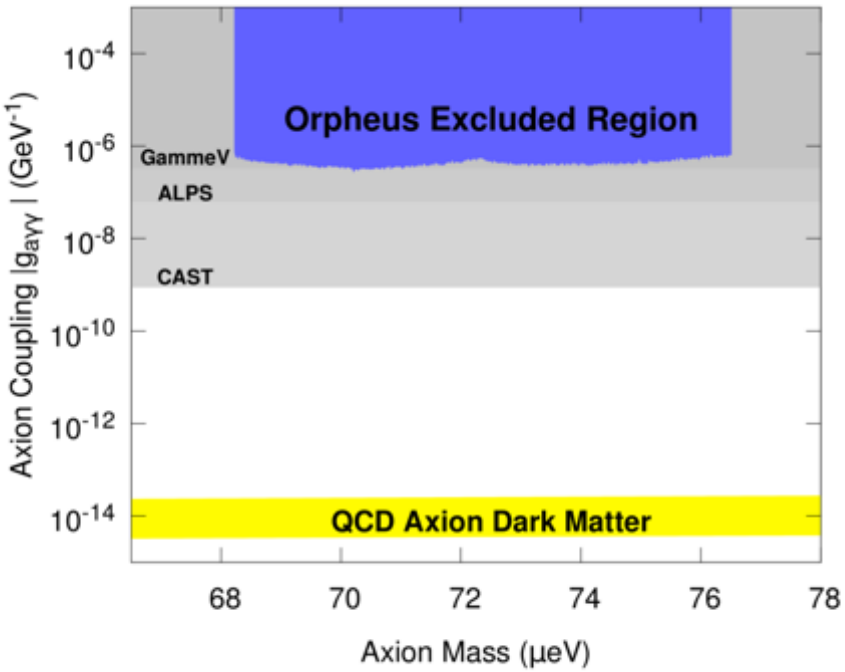

PhysRevD.91.011701

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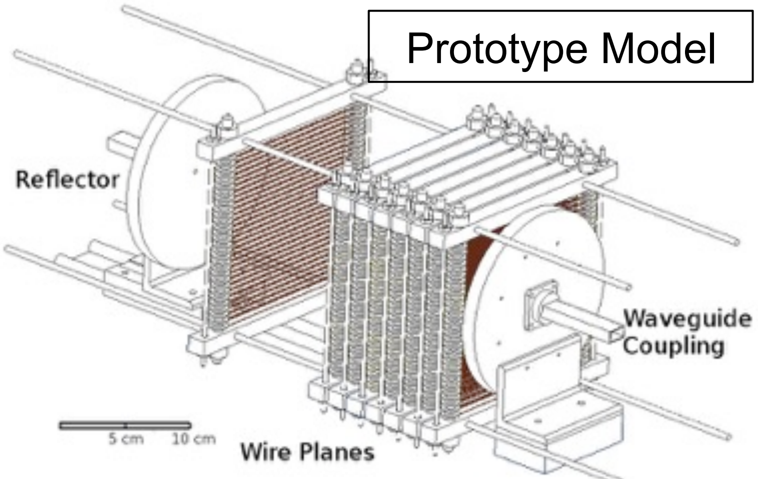
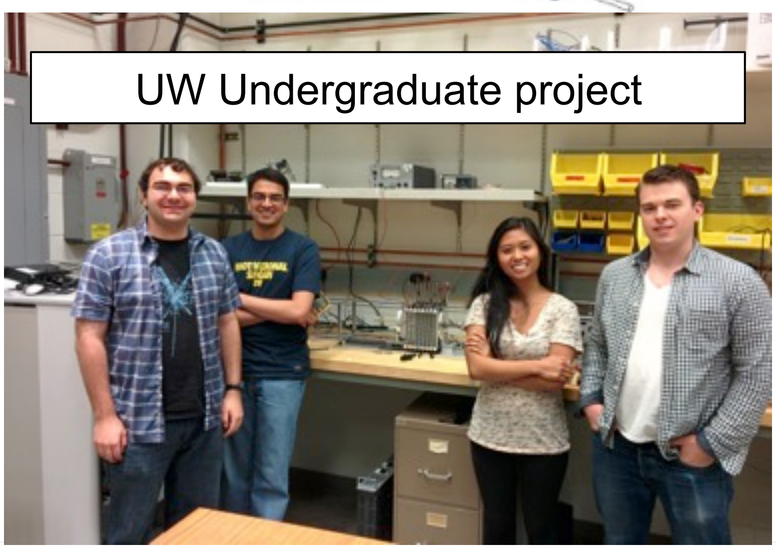
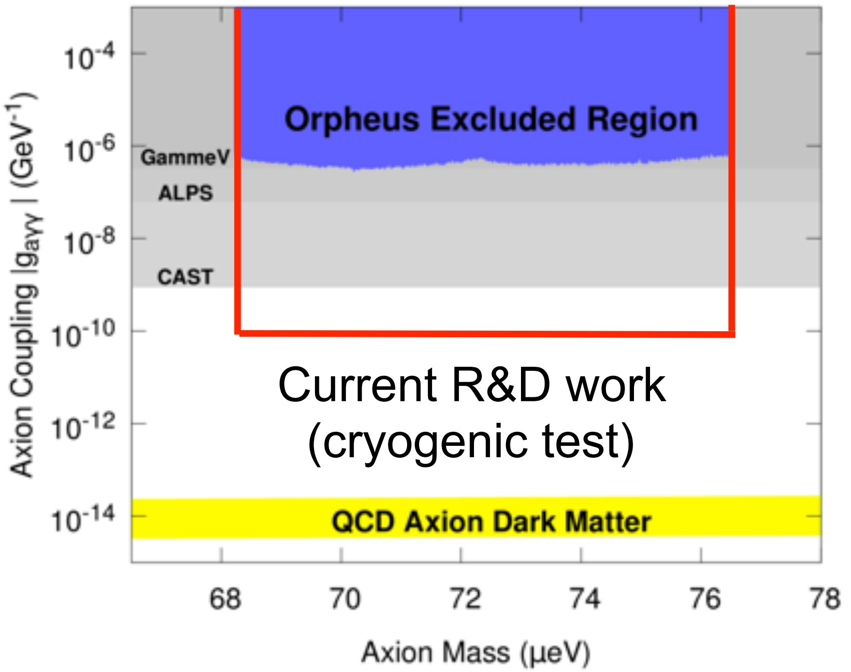


UW Undergraduate project





PhysRevD.91.011701

System potentially good to much higher frequencies (40 GHz or more)

Going beyond Standard Quantum Limit

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

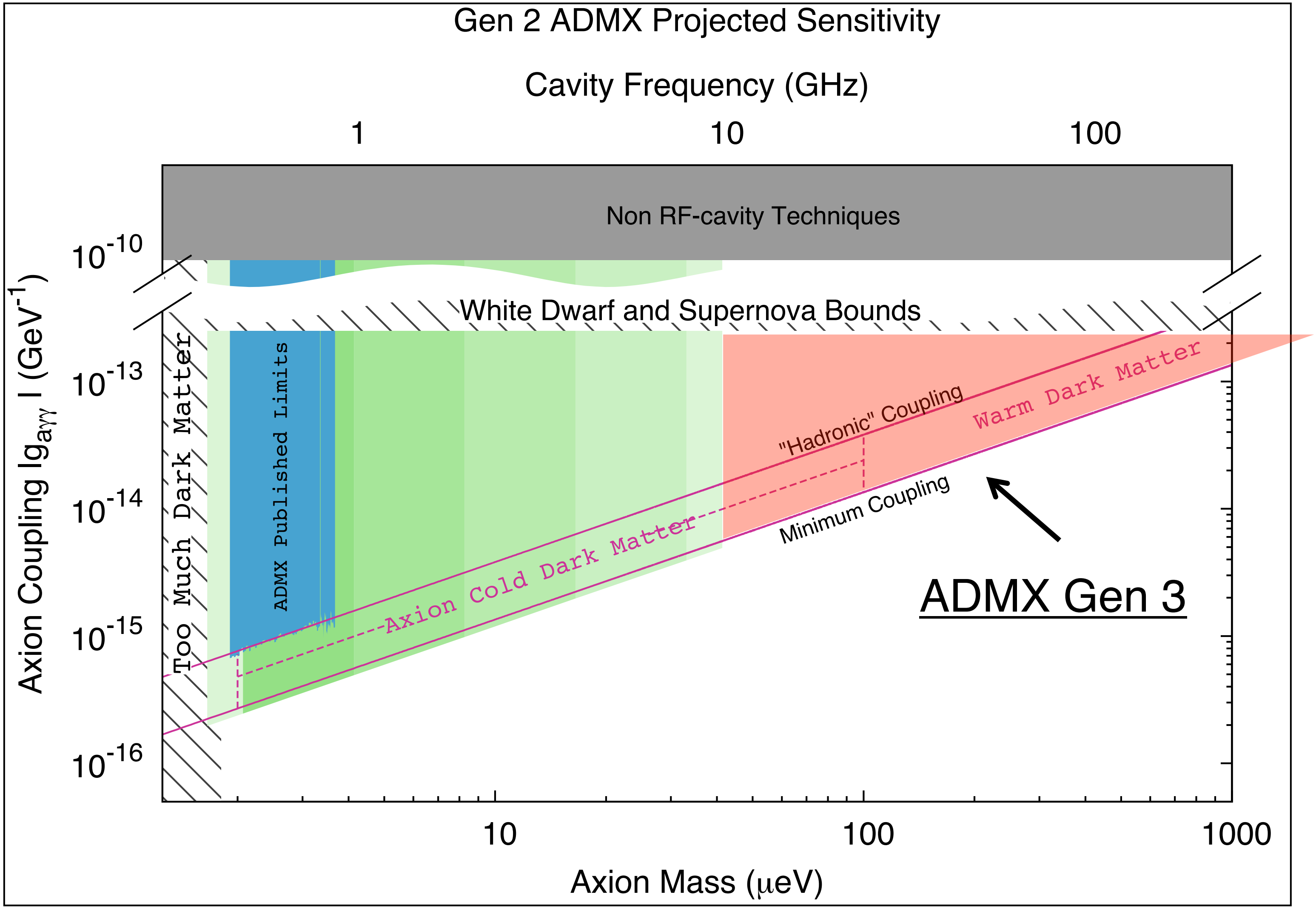
The SQL can be evaded by:

- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)
- Currently focus of R&D (LLNL, FNAL, UC Berkeley)

- S.K. Lamoreaux et al. (PhysRevD.88.035020)

ADMX Generation 3

Long term goal is to detect or rule out axion as primary dark matter candidate.



Summary & Conclusions

Axions: solve the Strong-CP problem and are a compelling DM candidate

The ADMX Gen 2 project A narrow band experiment with concurrent R&D

Takes data in one mass range while developing systems for higher masses.

Finished commission run.

Anticipate 6 year data taking run starting Feb 2017.

Technologies that are under active development (haloscopes):

1. Microwave Cavities:
    - High-Frequency, Large-Volume Tunable Systems with high Q
2. RF Detectors: Quantum Limited (0.25 – 10 GHz): SQUIDs & JPAs
3. Beyond several GHz the standard quantum limit begins to dominate
    - Employ Squeezed States and Eventually Single-Photon-Counters
4. Large Magnets can increase axion conversion signal.

Plug for upcoming workshop…

2nd Workshop on Microwave Cavities and Detectors for Axion Research

January 10-13th, 2017 at the Lawrence Livermore National Laboratory Open Campus

Funded by Heising-Simons Foundation (funds for travel & lodging)

http://indico.fnal.gov (search under "axions" and you'll see this one and last years)

Questions?